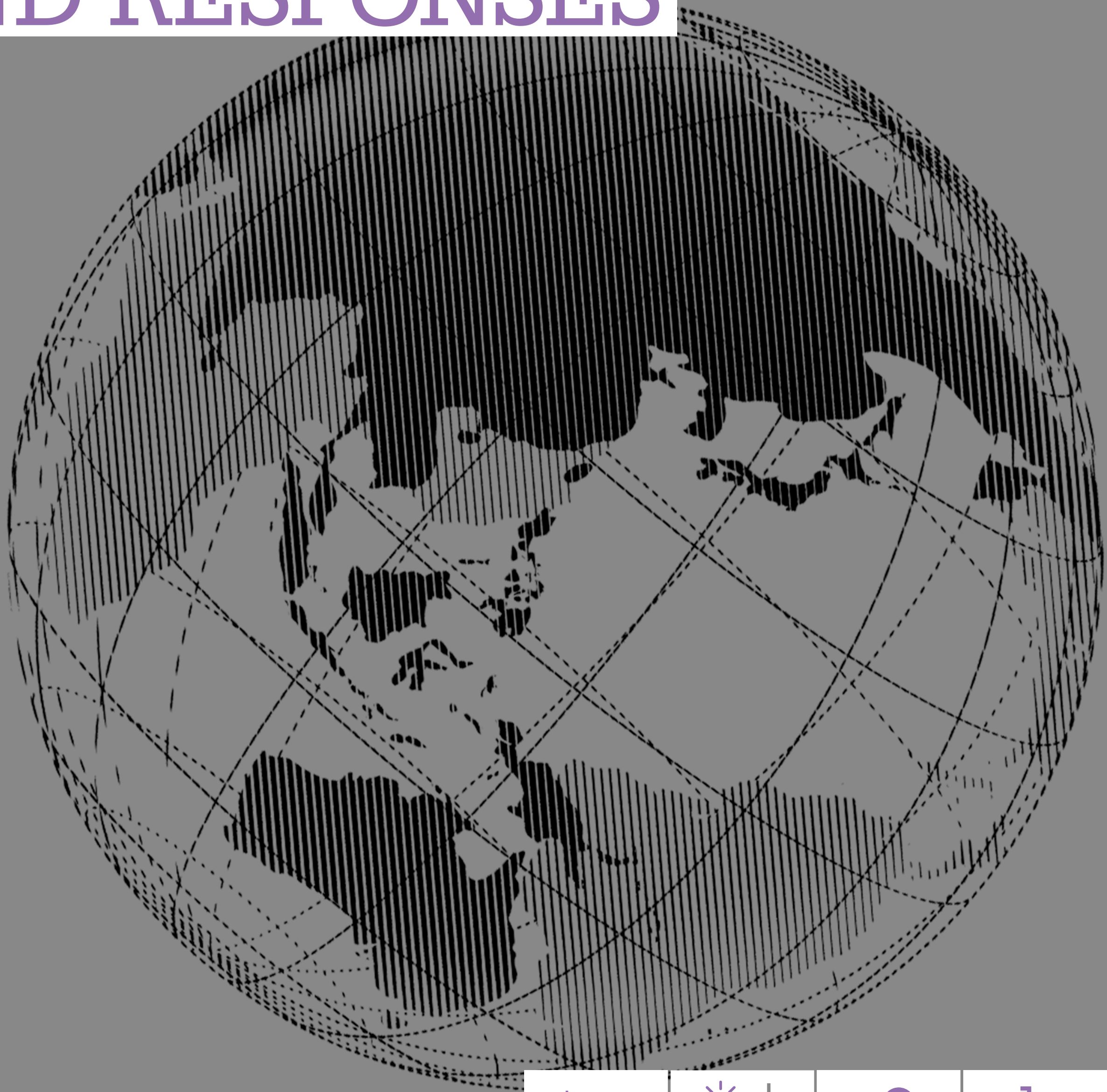
CLIMATE
COMMISSION

# THE CRITICAL DECADE 2013

## CLIMATE CHANGE SCIENCE, RISKS AND RESPONSES



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# PREFACE


The Climate Commission brings together internationally renowned climate scientists, as well as policy and business leaders, to provide an independent and reliable source of information about climate change to the Australian public.

This is the Climate Commission's 26th publication and follows a series of reports on the science and impacts of climate change, the opportunities in Australia associated with taking action to reduce greenhouse gas emissions, and international action on climate change.

Two years ago in its report *The Critical Decade: Climate science, risks and responses*, the Climate Commission stated that this decade, 2011-2020, is the decade to decisively begin the journey to decarbonise our economy, thereby reducing the risks posed by climate change. One quarter of the way through the critical decade we present here an update of our current knowledge of climate change – the scientific evidence, the risks to our communities and the responses required to prevent significant harm. The report authors have periodically provided similar accessible updates on the science of climate change. The Climate Commission believes that these reports are important to ensure that the Australian public has access to authoritative and relevant information.

The report begins by describing the basics of climate change science – how the climate works and how human activities are affecting climate. *Section 2* examines observations of the changing climate and what is expected for the future. *Section 3* focuses on what these changes in the climate mean for people and natural ecosystems. The final section explains how an understanding of science and risks can inform our responses.

The information in this report is compiled from the most up-to-date, authoritative sources available, drawing on the peer-reviewed scientific literature. A reference list is included at the end of the report for those who would like further information on a particular subject.

2013 is an important year for climate science. In September the Intergovernmental Panel on Climate Change (IPCC), the world's foremost authority on climate science, will release the first of three reports that taken together form the Fifth Assessment Report. These reports will provide an update of knowledge on the scientific, technical and socio-economic aspects of climate change at a global and regional scale. The IPCC brings together thousands of scientists from different disciplines to provide an authoritative global assessment. The Climate Commission will provide briefings on these reports to ensure that this IPCC information is contextualised and accessible for the Australian public.

We thank our fellow Commissioners and the Science Advisory Panel, who reviewed this report.

The authors retain sole responsibility for the content of the report.

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Climate Commissioner

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# KEY FINDINGS:

Two years ago the Climate Commission warned that 2011-2020 is the 'Critical Decade' for tackling climate change. In particular, this is the Critical Decade for turning around rising emissions of greenhouse gases, and putting us on the pathway to stabilising the climate system.

**One quarter of the way through the Critical Decade, many consequences of climate change are already evident, and the risks of further climate change are better understood. It is clear that global society must virtually decarbonise in the next 30-35 years. This means that most of the fossil fuel reserves must stay in the ground.**

1. **Our understanding of the climate system has continued to strengthen.**
   - Over the past half-century, rapid changes have been observed across the world in many features of the climate system, including heating of the ocean and the air; changing rainfall patterns; reduction in the area of Arctic sea ice; mass loss of polar ice sheets; increasing sea level; and changes in life cycles and distribution of many plants and animals.
   - There is a very strong consensus that the climate is changing and that human activities, like the burning of fossil fuels, are the primary cause.
   - Scientists are now moving to new challenges, for instance, improving our understanding of shifting rainfall patterns and of potential abrupt or irreversible changes in major features of the climate system.
2. **We are already seeing the social, economic and environmental consequences of a changing climate.** Many of the risks scientists warned us about in the past are now happening.
   - **Heatwaves:** The duration and frequency of heatwaves and extremely hot days have increased across Australia and around the world. The number of heatwaves is projected to increase significantly into the future.
   - **Bushfire weather:** Climate change has already increased the risk of extreme fire weather in some parts of Australia, especially the populous southeast.
   - **Rainfall** patterns are shifting. The southwest corner of Western Australia and much of eastern Australia has become drier since 1970. The southwest and southeast corners of Australia are likely to remain drier than the long-term average or become even drier.
   - **Sea-level rise:** Global average sea level is now rising at a rate of 3 cm per decade and will continue to rise through the rest of this century and beyond, contributing to an increased frequency of coastal flooding around the world including Australia. For example, Fremantle has already experienced a three-fold increase in high sea level events since 1950.
3. **The changing climate poses substantial risks for health, property, infrastructure, agriculture and natural ecosystems.**
   - **Health:** Heat causes more deaths than any other type of extreme weather event in Australia. Increasing intensity and frequency of extreme heat poses health risks for Australians and can put additional pressure on health services. Changes in temperature and rainfall may allow mosquito-borne illness like dengue fever to spread south.
   - **Property and infrastructure** across Australia has been built for previous climatic conditions and much of it is ill-prepared to cope with increasingly frequent and/or intense extreme weather.

- **Agriculture:** Changing rainfall patterns and increasing risk of extreme heat and bushfire weather present challenges for Australian agriculture. Production of temperature- and water-sensitive broad-acre crops, fruit, vegetables and wine grapes needs to adapt to these changing growing conditions or move to locations where growing conditions are becoming more amenable for their production.
- **Natural ecosystems:** Many Australian plants and animals are already responding to climate change by changing their distributions and the timing of life cycles. Climate change, in combination with other stresses, is increasing the risk of species extinctions and threatening many iconic ecosystems including the Great Barrier Reef, Kakadu National Park and the alpine zone.

4. **One quarter of the way into the Critical Decade it is clear: some progress is being made globally to reduce emissions. However, far more will need to be done to stabilise the climate.** The decisions we make from now to 2020 will largely determine the severity of climate change our children and grandchildren experience.

- There has been meaningful global progress in the last two years. All major economies, including China and the United States, are putting in place solutions to drive down emissions and grow renewable energy. It will take some time to see the full impact of these policies.
- Carbon dioxide concentrations are at the highest level in over one million years. Despite global efforts they continue to increase at a rate much faster than at any other time in the recent geological record
- Most nations of the world, including Australia, have agreed that the risks of a changing climate beyond 2°C are unacceptably high. The temperature rise is already approaching 1°C above pre-industrial, nearly halfway to the 2°C limit.
- The best chance for staying below the 2°C limit requires global emissions to begin declining as soon as possible and by 2020 at the latest. Emissions need to be reduced to nearly zero by 2050.
- Stabilising the climate within the 2°C limit remains possible provided that we intensify our efforts this decade and beyond.

5. **Most of the available fossil fuels cannot be burned if we are to stabilise the climate this century.**

- The burning of fossil fuels represents the most significant contributor to climate change.
- From today until 2050 we can emit no more than 600 billion tonnes of carbon dioxide to have a good chance of staying within the 2°C limit.
- Based on estimates by the International Energy Agency, emissions from using all the world's fossil fuel reserves would be around five times this budget. Burning all fossil fuel reserves would lead to unprecendented changes in climate so severe that they will challenge the existence of our society as we know it today.
- It is clear that most fossil fuels must be left in the ground and cannot be burned.
- Storing carbon in soils and vegetation is part of the solution but cannot substitute for reducing fossil fuel emissions.

# INTRODUCTION

Two years ago the Climate Commission released its first major report, *The Critical Decade: Climate science, risks and responses.* The report, a comprehensive synthesis of the most recent climate change science, received significant traction in Australia and overseas. The phrase, '*the critical decade*', has become the defining mantra for the Climate Commission, emphasising the clear imperative of significant Australian and global action this decade.

Two years on, and one quarter of the way through the decade, we have systematically updated *The Critical Decade* in this report.

Evidence for a rapidly changing climate has continued to strengthen over the last two years: heating of the ocean and the air; changing rainfall patterns; rapid mass loss of ice sheets and sea ice; increasing sea level; and changes in life cycles and distribution of plants and animals.

Importantly, the basic physical science has not changed. For years now there has been a clear and strong global consensus from the scientific community that the climate is changing, that human activities are the primary cause, and that the consequences for humanity of increasing destabilisation of the climate system are extremely serious.

Perhaps the most important development over the past two years has been the improved understanding of the influence of climate change on extreme weather events. The publication of the Intergovernmental Panel on Climate Change (IPCC) special report *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (the 'SREX' report; IPCC, 2012) has provided authoritative information on our evolving understanding of the climate change-extreme weather link. The Commission's recent report *The Critical Decade: Extreme weather* explores this link in detail.

It is clear that the climate system has already shifted, changing conditions for all weather. While extreme weather events have always occurred naturally, the global climate system is hotter and wetter than it was 50 years ago. This has loaded the dice toward more frequent and forceful extreme weather events.

Climate change is already having a significant impact on Australians and people around the world, primarily through its influence on extreme events, on human health, agriculture, fresh water supplies, property, infrastructure, and the natural ecosystems upon which our economy and society depends. Whereas the consequences of climate change were once a matter for the future, as the climate shifts we are already experiencing the consequences.

The progress over the last two years adds a greater richness and depth to our understanding and further reinforces the underlying climate science. However, more research is required to continue to improve our knowledge about risks that are particularly important for informing policy development, decision making and enhancing preparedness.

This report is separated into four sections. *Section 1* examines the physical science of climate change, explaining how the climate system works and how human activities are

influencing the climate. *Section 2* describes the changes in the climate system that have already been observed, particularly in the last 50 years. It paints a picture of what we can expect into the future, considering both scientists' projections and the uncertainties around them, as well as looking at previous climates in Earth history. *Section 3* outlines the impacts of a changing climate and provides a snapshot of this for key sectors, as well as summaries for each Australian state and territory. *Section 4* is perhaps the most important. Given what science can tell us about the changing climate, what needs to be done to stabilise the climate?

The Climate Commission provides Australians with accessible and up-to date information on climate change. This information is critical to ensure that communities, emergency services, health care providers, businesses and governments can make informed decisions. In addition to this detailed report, the Climate Commission has produced a range of supplementary materials, accessible on our website. They include:

- A short summary document
- Infographics and diagrams
- A summary video animation
- State and territory fact sheets.

On the final two pages of this report is a list of common questions about climate change. These are included to support readers in taking the information in this report and communicating it to family, friends and colleagues. The decisions that are made this decade will be crucial to Australia's future and the Climate Commission encourages all Australians to participate actively in those decisions.

# CHAPTER 1: THE SCIENCE OF CLIMATE CHANGE

## 1.1 The basics: climate and weather

Climate is often confused with weather. The two are obviously related, but it is important to understand the difference. The oft-quoted phrase 'climate is what you expect, but weather is what you get' describes the relationship quite well. Weather is what we experience on a day-to-day basis. Weather is inherently variable, and includes extreme weather events such as hot days, heavy rainfall and storms, which can have serious impacts on our health and well-being.

Variability in weather can also occur over longer periods – weeks and months. *Figure 1* shows the year-by-year annual rainfall across Victoria. Although we can calculate a long-term average amount of rainfall (the red line in the figure), this is certainly not what occurs every year (the vertical bars in the figure). There is large variability around this average, and even from decade to decade.

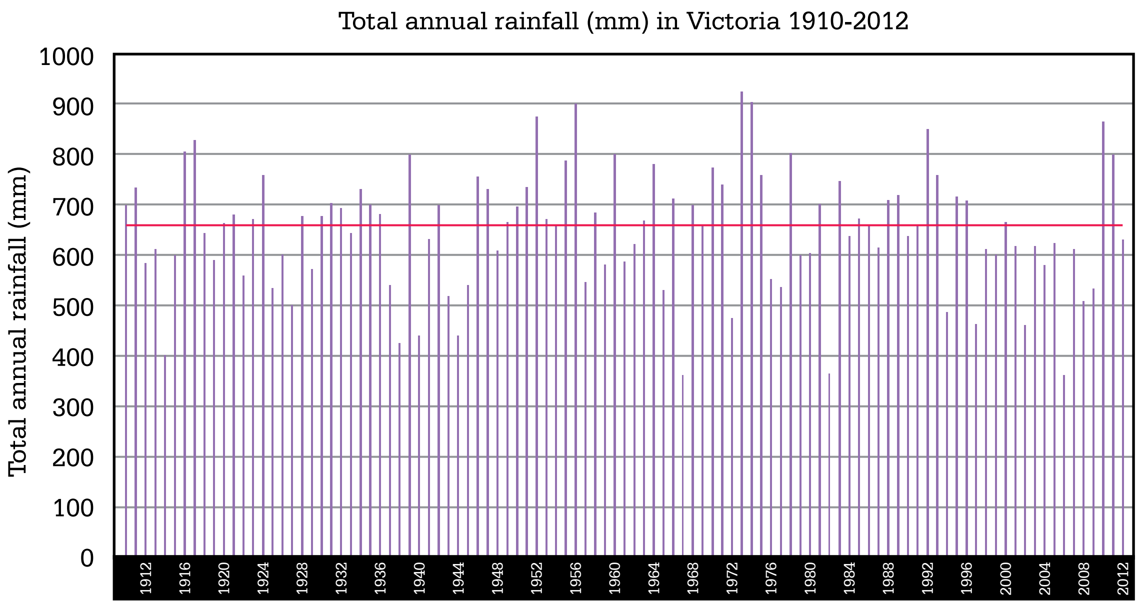


**Figure 1:** Time series of total annual rainfall (mm) in Victoria from 1910 through 2012. The red horizontal line is the average for this period.

**Source:** BoM, 2013a

Climate, on the other hand, is weather averaged over a long period of time, usually at least three decades or longer. Including an estimate of variability around the average climate provides the 'climatic range' within which societies live in the present and plan for the future. For example, Canberra has a much higher seasonality of temperature – winters are much colder than summers – than Darwin, where temperatures vary little through the year. The opposite is true for rainfall. Darwin has distinct wet and dry seasons while Canberra has a more even distribution of rainfall throughout the year. This affects how residents plan and build their infrastructure, and how basic resources such as water are provided. *Figure 2* shows the distribution of Australia's population and our most important crop production areas. There is no doubt that climate plays an important role in determining this distribution – much of Australia is simply too dry to support large numbers of people or large areas of cropland.

But climate is more than statistics – the climate is part of the Earth System, which includes the basic physics, chemistry, geology and biology that create the environment at the Earth's surface – the energy balance; the circulation patterns of the two great fluids at the surface, the atmosphere and the ocean; the global cycles of water and of critical elements like carbon and nitrogen; and the ways in which biological processes interact with these physical and chemical processes. The climate makes life possible on Earth, and, in turn, life influences how the climate works. Humans are a part of the Earth System, and since the Industrial Revolution, but especially in the past 60 years, our activities have begun to influence the climate at the global level. In fact, we are changing the fundamental energy balance of the Earth, and as a consequence we are changing the climate in many significant ways.

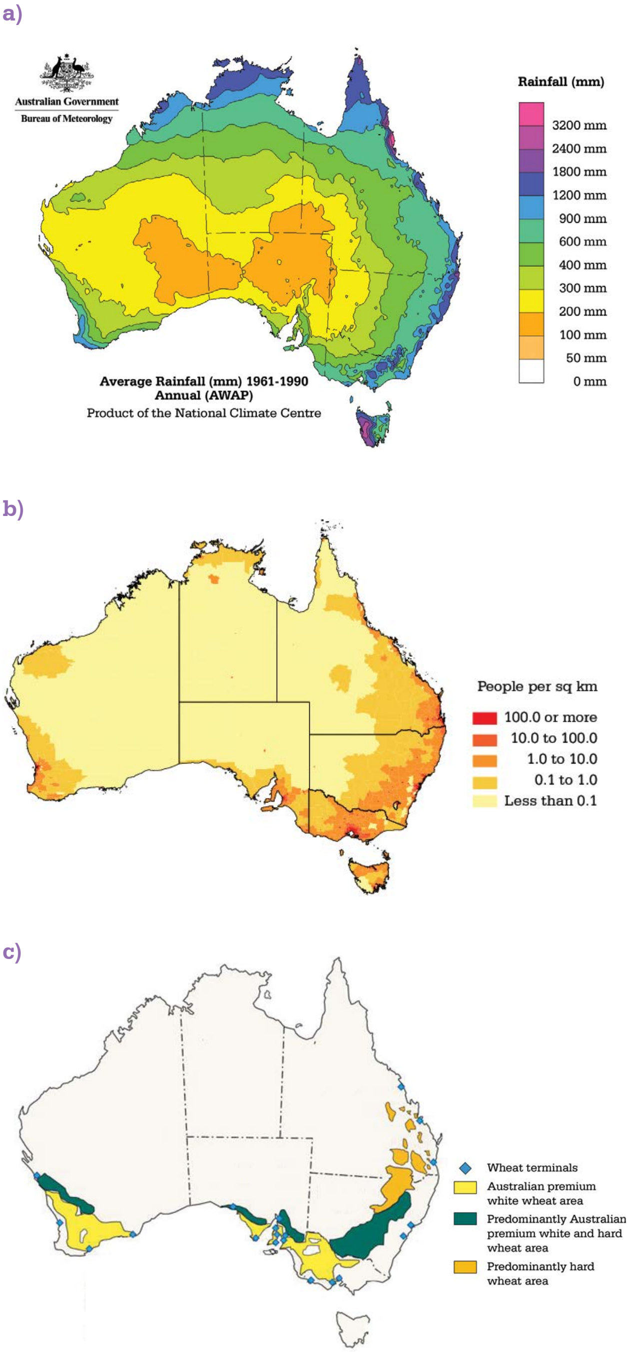


**Figure 2:** Map of Australia showing (a) average annual rainfall over the continent, (b) Australia's population density and (c) Australian wheat growing regions.

**Source:** (a) Produced by BoM for this report; (b) ABS, 2013a; (c) ABARES, 2012a

## 1.2 How does the climate system work?

The climate system is comprised of the ocean, the atmosphere, land and ice – and the processes that move and transform energy and materials around the surface of the Earth (*Figure 3*).

One of the most important features of the climate system is the greenhouse effect, which modifies the energy balance at the Earth's surface (Pierrehumbert, 2011). The effect results from the characteristics of several gases in the atmosphere, and, as the name indicates, mimics the effect of a glass greenhouse that allows in energy from the sun and traps some of the heat generated from that incoming energy to warm the interior of the greenhouse.

*Figure 4* shows how the greenhouse effect works in the atmosphere. Incoming light and higher energy radiation from the sun penetrate through the Earth's atmosphere, with some of this radiation reflected back out to space by clouds and bright surfaces, such as the white polar ice sheets. But much of this incoming energy is absorbed by land and water at the Earth's surface.

To maintain its energy balance, the Earth emits energy back into space equivalent to the energy which is absorbed. But this energy is emitted in a different form to how it arrived from the sun, as heat, not light. This is where the greenhouse gases come in. Although they are mostly transparent to the incoming solar radiation, they trap some of the outgoing heat, keeping the Earth's atmosphere, and hence the surface also, warmer than they would otherwise be. The most important long-lived greenhouse gases are carbon dioxide ($CO_2$), methane and nitrous oxide.

This natural greenhouse effect is very important. Without it, the Earth's surface would be over 30°C colder than it is today, and would be frozen, even at the equator. Under these conditions, life as we know it, and certainly human life, could not exist.

In addition to greenhouse gases, other factors can affect the energy balance and hence the climate. These include very small variations in the amount of incoming energy from the sun, which can either warm or cool the climate slightly. Very large volcanic eruptions can also affect the energy balance by injecting into the upper atmosphere large amounts of small particles, which reflect some of the incoming solar radiation back into space and cool the climate for a year or two following an eruption.

Feedbacks are another important feature of the climate system (*Box 1*). A feedback occurs when an initial change imposed on a system triggers responses within the system that either amplify or dampen the initial change. A cooling system in a building is an everyday example of a system with feedbacks. When the room temperature rises too high on a warm summer day, a thermostat activates an air conditioner that brings the room temperature back down to within pre-determined limits. This is an example of a dampening feedback.

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HUMANS ARE A PART OF THE EARTH SYSTEM, AND OVER THE PAST FEW CENTURIES – ESPECIALLY THE PAST 60 YEARS – OUR ACTIVITIES HAVE BEGUN TO INFLUENCE THE CLIMATE AT THE GLOBAL LEVEL

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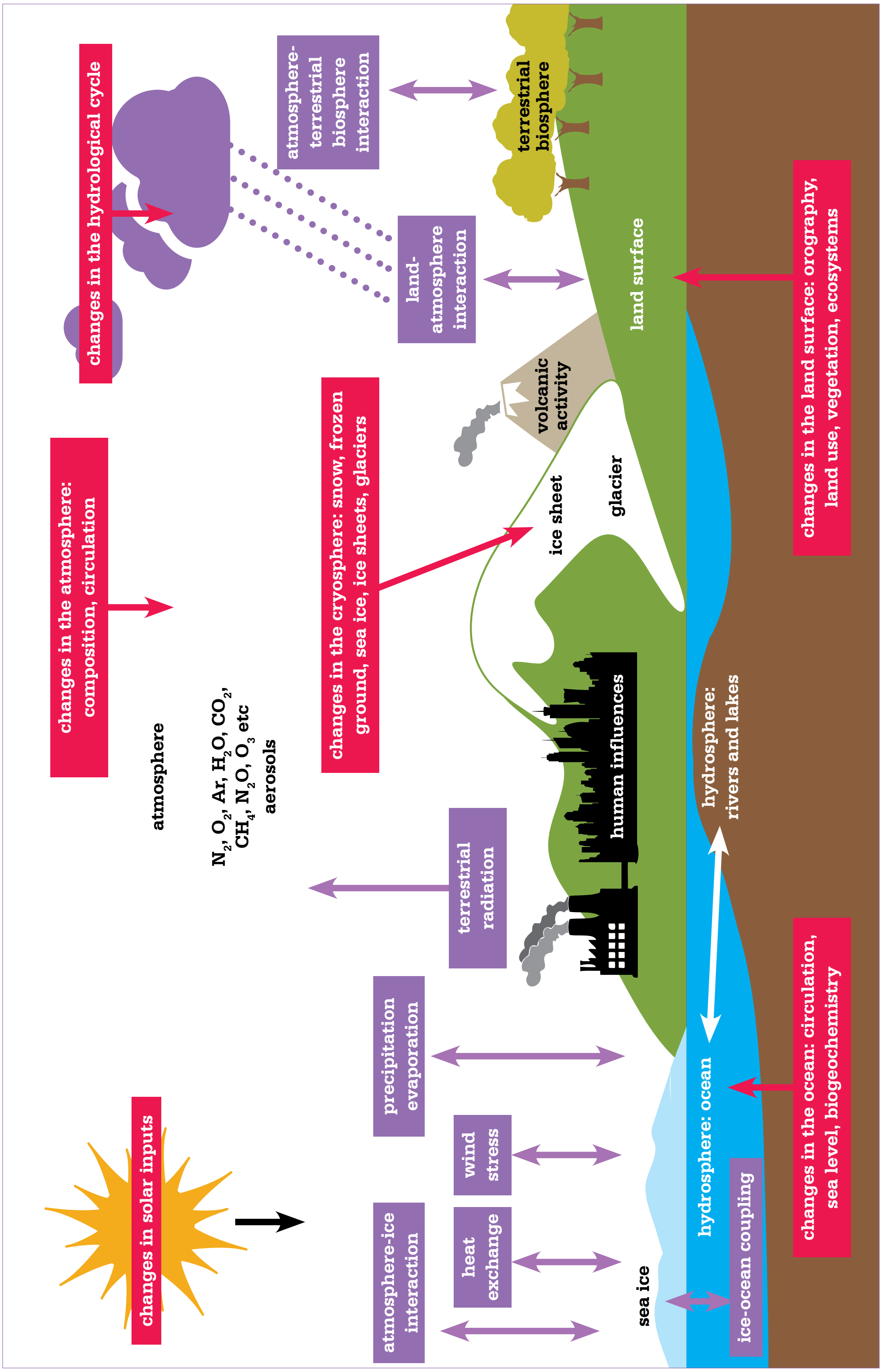



**Figure 3:** The main components and processes of the climate system.

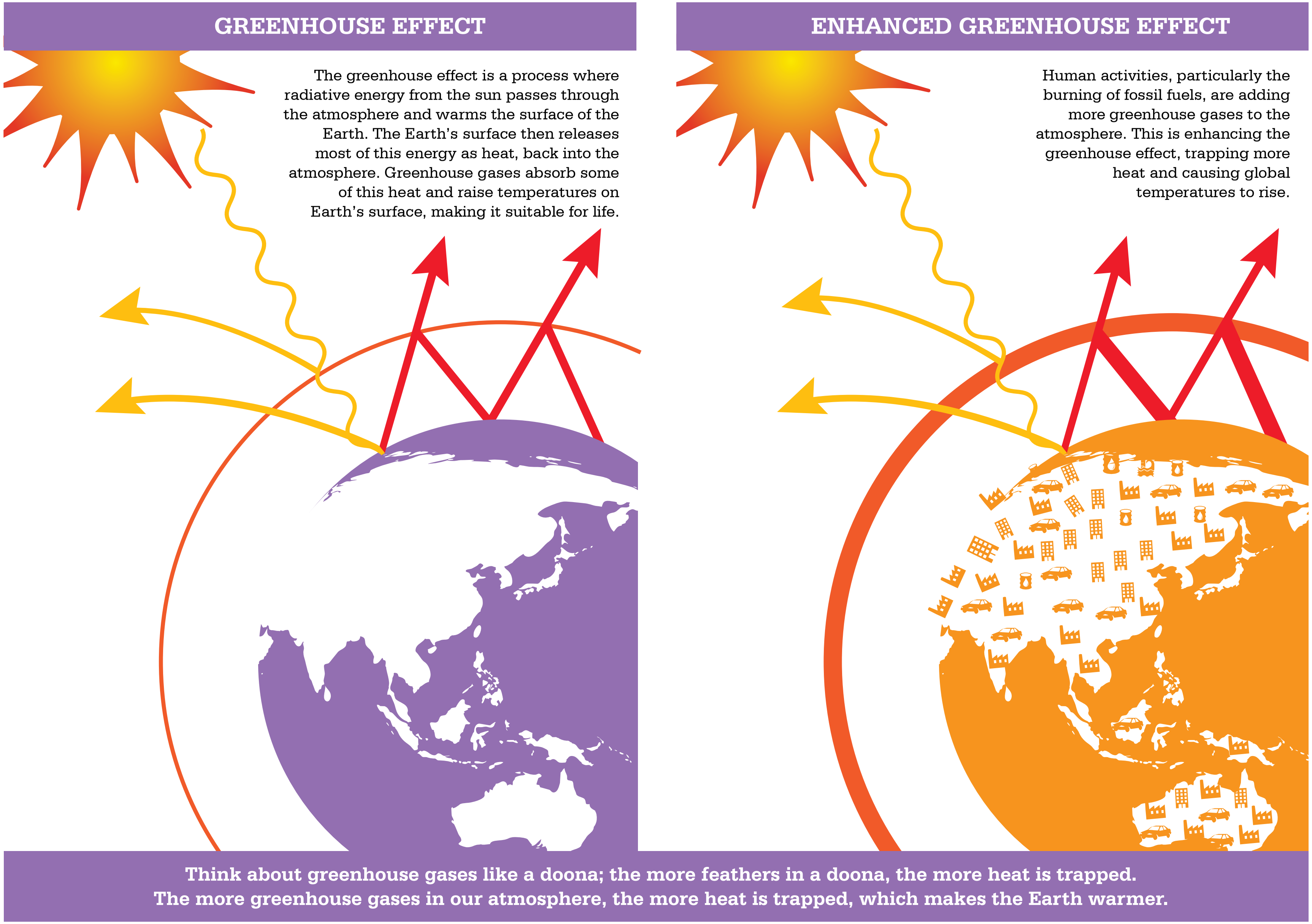



**Figure 4.** The influence of increased concentrations of greenhouse gas emissions on the greenhouse effect.

**Box 1: Feedbacks in the climate system**

Feedbacks are crucial to understanding how small changes to the Earth's energy balance can lead to larger-than-expected changes in the climate. A very important question is how much will feedbacks amplify or dampen the initial warming of the climate caused by the increasing concentration of greenhouse gases in the atmosphere?

Scientists often differentiate feedbacks in the climate system as 'fast feedbacks', those that operate over time periods of days, weeks to years or decades, and 'slow feedbacks', those that take centuries or millennia to unfold. The two most important fast feedbacks are the increasing water vapour in the atmosphere and the change in the cloud cover. *Figure 5a* shows how the water vapour feedback works to amplify the initial warming from an increase in greenhouse gases in the atmosphere. Cloud feedbacks are more complex, and can be either amplifying or dampening depending on the nature of the clouds and where they are located in the atmosphere.

The most important slow feedbacks are associated with the change in ice and snow cover at the Earth's surface and with shifts in the distribution of large ecosystems called 'biomes,' for example the boreal forests of Canada. Both of these changes affect the amount of solar radiation that is absorbed or reflected by the Earth's surface. Dark surfaces absorb sunlight, increasing the amount of warming, while light surfaces reflect sunlight, reducing the amount of warming. *Figure 5b* shows how a decrease in ice cover works to amplify warming, by increasing the surface area that absorbs rather than reflects sunlight. The biome feedback is most important in the northern high latitudes. As the climate warms, forests spread at the expense of the much shorter tundra vegetation. In the northern hemisphere spring, the sunlight 'sees' more dark trees and less snow-covered tundra and so the land absorbs more sunlight, amplifying the initial warming.

An ice-covered Arctic Ocean is a large white surface that reflects sunlight. The loss of summer Arctic sea ice uncovers more dark ocean water that, in turn, absorbs more sunlight. This is another example of an amplifying feedback that drives further warming in the northern high latitudes, which in turn increase the rate of loss of sea ice. The loss of Arctic sea ice is happening so rapidly that it is often considered to be a fast feedback.

FEEDBACKS ARE CRUCIAL TO UNDERSTANDING HOW SMALL CHANGES TO THE EARTH'S ENERGY BALANCE CAN LEAD TO LARGER-THAN-EXPECTED CHANGES IN THE CLIMATE.

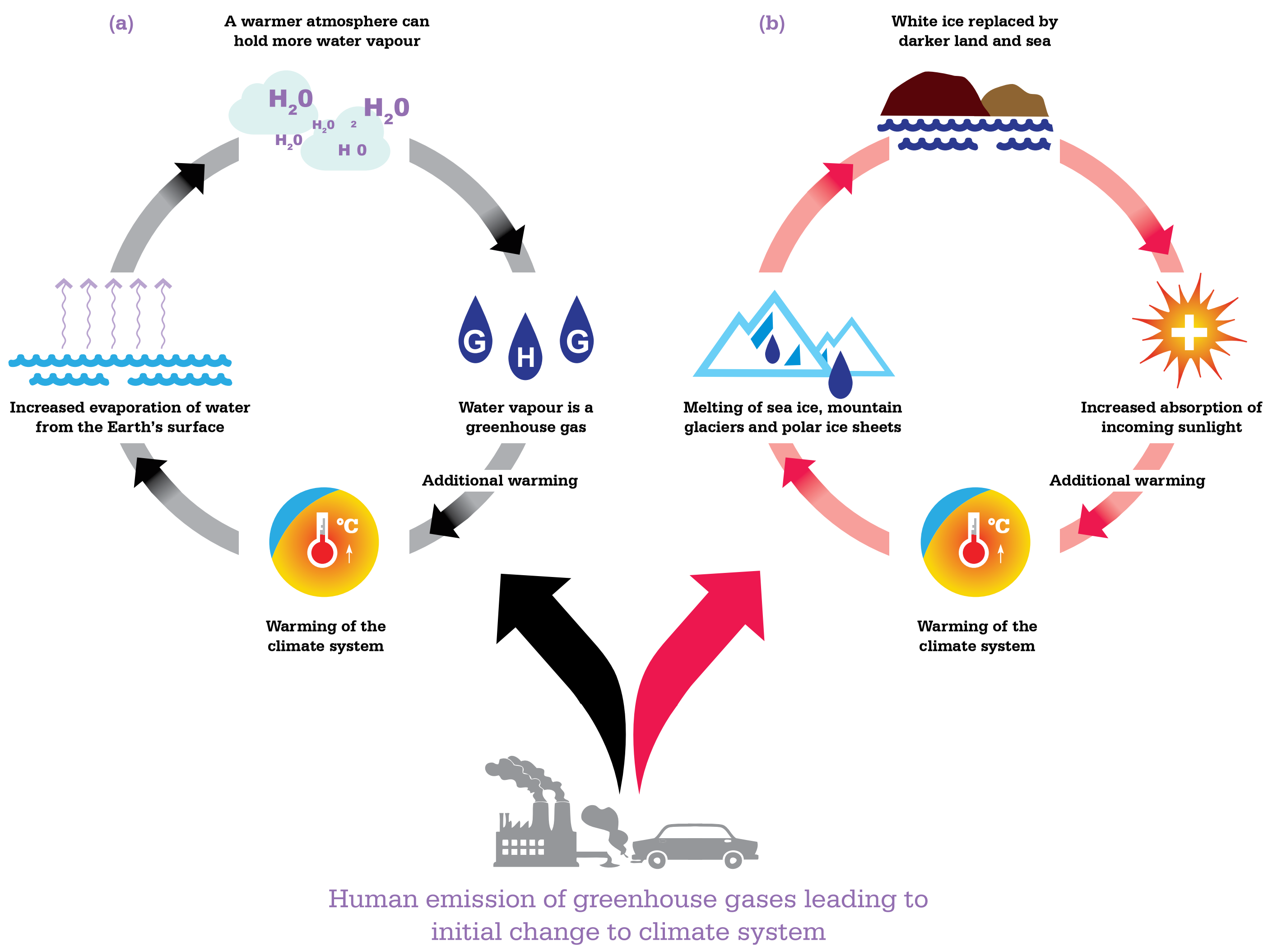



**Figure 5:** The basic features of (a) the temperature-water vapour feedback; and (b) the ice-albedo feedback.

## 1.3 How are human activities changing the climate?

Human activities have affected the climate for a long time, but it is only after the Industrial Revolution, and especially since 1950, that human activities have become so significant that they are changing the climate on a global scale. The most important human influence is the emission of greenhouse gases to the atmosphere from the burning of fossil fuels; human activities have increased the amount of carbon dioxide in the atmosphere by 40% since the beginning of the Industrial Revolution.

The trends in the concentrations of $CO_2$, methane and nitrous oxide since 1750 are shown in *Figure 6*, with the much longer trend in concentrations over the past 10,000 years shown for context (IPCC, 2007). The additional greenhouse gases that have accumulated in the atmosphere since the beginning of the Industrial Revolution, and especially since 1950, are trapping more heat within the Earth's atmosphere (*Figure 4*). This heat builds up throughout the lower atmosphere, at the Earth's surface and within the oceans.

Other human activities also influence the climate. Local and regional air pollution involves the emission of aerosols, which are small particles, to the lower atmosphere. These mainly affect the climate by causing cooling, thus partially counteracting the effect of greenhouse gas emissions, but they can also affect the amount and distribution of rainfall (Rotstayn et al., 2007; Cai et al., 2007). Land-use change, such as the conversion of forest to cropland, also affects the local and regional climate by altering the amount of sunlight that is absorbed or reflected by the land surface and changing the rate of the evapotranspiration. Urbanisation also has a significant effect on local and regional climates (Cleugh and Grimmond, 2011).

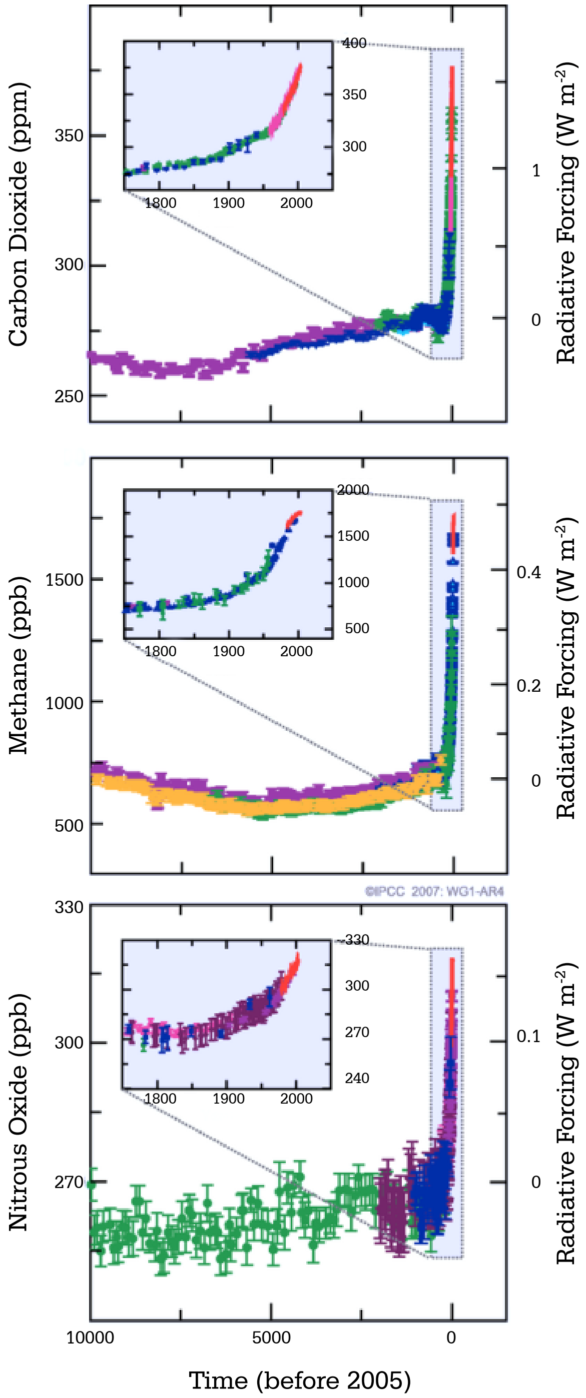



**Figure 6:** Atmospheric concentrations of $CO_2$, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings are shown on the right hand axes of the large panels.

**Source:** IPCC, 2007

*Figure 7* shows the relative importance of factors that affect the Earth's energy balance for the period from 1750, before the beginning of the Industrial Revolution, to 2005 (IPCC, 2007). Greenhouse gas emissions are the most important human influence over this period, with $CO_2$ being the most important of these. Aerosols, which have a net cooling effect, are estimated to have approximately offset the warming effects of the non-$CO_2$ greenhouse gases. Land-use change has a small cooling effect globally. When all of these factors are combined (called the 'net radiative forcing'; see glossary), human activities have a significant warming effect on the climate system. By comparison, the natural variation in solar radiation from 1750 to 2005 is also shown in *Figure 7*, and it is much smaller than the net effect of human activities on the climate.

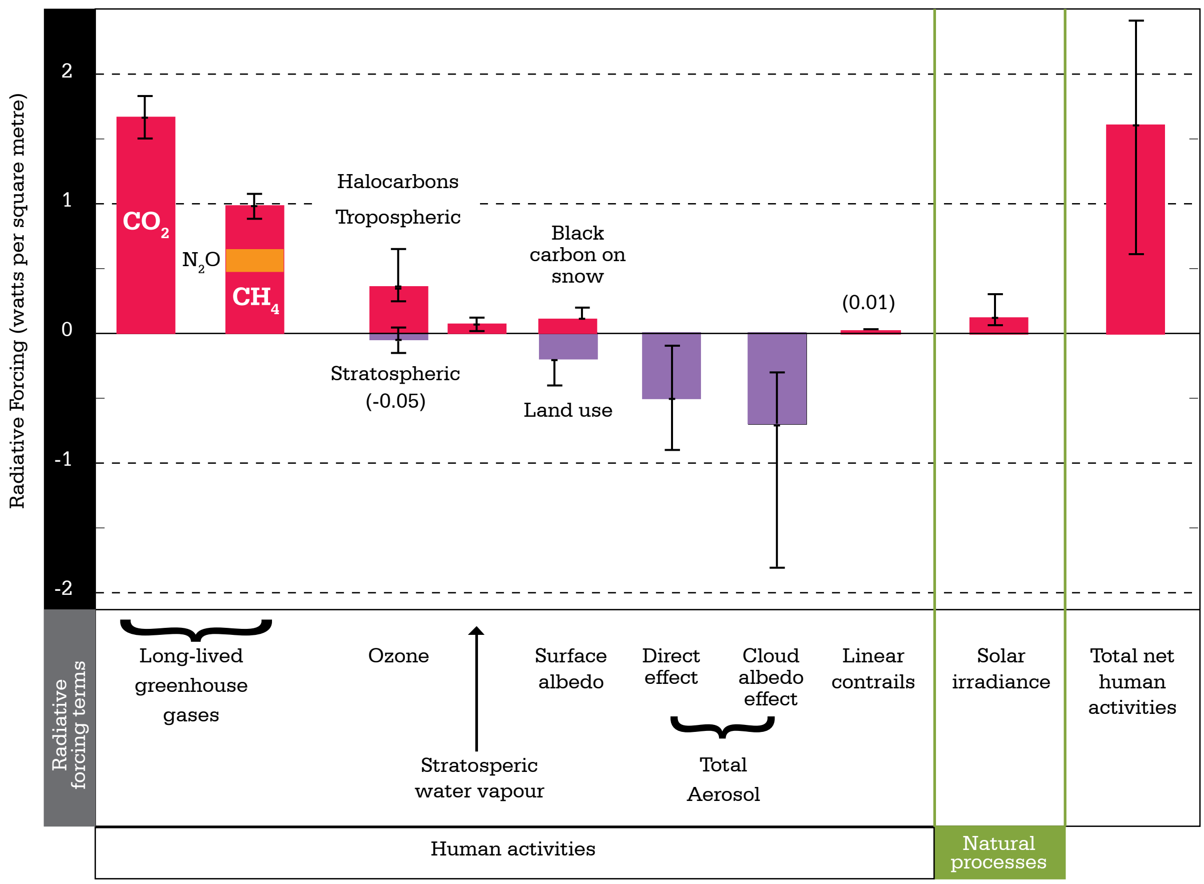



**Figure 7:** The relative importance of factors that affect the Earth's energy balance. Global average radiative forcing estimates and ranges in 2005 for anthropogenic $CO_2$, methane, nitrous oxide and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its ranges (90% likelihood) are also shown. These require the summing of asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails (vapour trails that form behind aircraft) does not include other possible effects of aviation on cloudiness.

**Source:** IPCC, 2007

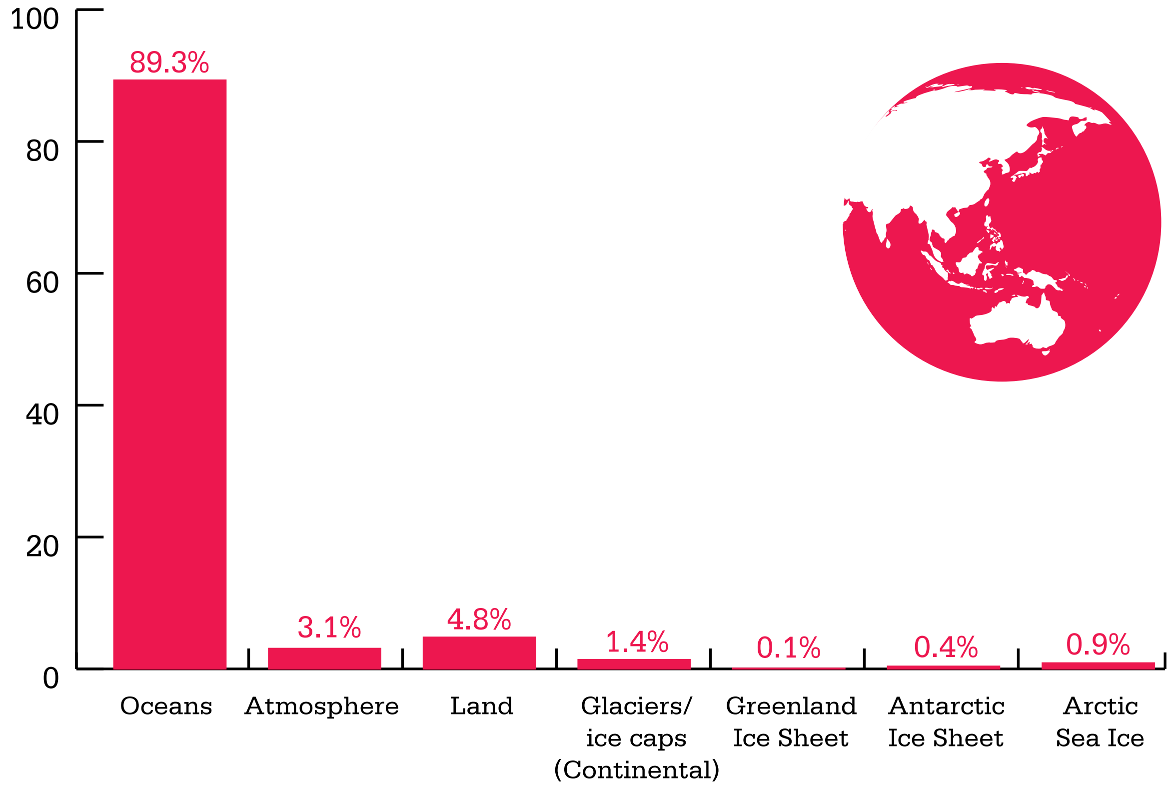



**Figure 8:** The partitioning of the extra heat from the enhanced greenhouse effect to the various parts of the climate system for the period 1961-2003. As indicated in the graph, the ocean has taken up about 90% of the extra heat in the climate system.

**Source:** IPCC, 2007

*Figure 8* shows how the additional heat from the enhanced greenhouse effect has thus far been distributed through the climate system. The most striking feature of this distribution is the dominance of the ocean, which has taken up about 90% of the additional heat (IPCC, 2007). In contrast, the atmosphere has absorbed only about 3%. This makes the uptake of heat by the ocean the best single indicator of global warming. The ocean takes up much more heat than the atmosphere because water can absorb much more heat than the gases in the air, and the ocean covers more than two-thirds of the Earth's surface at depths that can be up to several kilometres.

# CHAPTER 2: OBSERVATIONS AND PROJECTIONS

## How is the climate changing and how will it change in the future?

The accumulation of heat in the climate system has already led to significant changes. The temperatures of the air and the oceans have increased, rainfall patterns have changed and snow and ice are being lost. Biological systems can also act as indicators of climate change. Many species have shifted their geographical distributions and changed behaviour in ways consistent with the observed change in the climate.

This section describes the observed changes in many features of the climate system, reinforcing our understanding of the physical processes described in *Section 1*. Based on this physical understanding, we can then estimate, or 'project', how the climate system might evolve over the coming decades and centuries, given assumptions about the rate at which greenhouse gases continue to increase in the atmosphere.

### 2.1 Observations of a changing climate

#### Air temperature

Changes in average air temperature over long periods of time are often used as an indicator of changes in the state of the climate system. Changes in extreme temperatures and other aspects of extreme weather are often more relevant in terms of their impacts on people, infrastructure and ecosystems. Changes in extreme weather are described in detail in *Section 3*.

Over the last 50 years air temperature has been increasing and every decade has been warmer than the decade before. In fact, 2000-2009 was the hottest decade since records began. *Figure 9* shows the time series of annual average air temperature from 1880, when enough modern instrumental records were available to calculate a global average, through to 2012. There is a high degree of variability from year-to-year, and even from decade-to-decade, in the record. However, from about 1970, the long-term temperature trend has been strongly upward, consistent

with the increase in the rate of greenhouse gas emissions since the mid-20th century. The rise in global average temperature over the past century has been about 0.8°C.

The air temperature trend for Australia over the last century largely mirrors the global trend (*Figure 10a*), with a rise in average temperature of about 0.9°C from 1910 to the present. The temperature increases have been larger in the interior of the continent and lower along the coasts (*Figure 10b*).

There has been some discussion in the scientific community recently about the so-called 'plateau' in the surface air temperature trend over the last 10-15 years, as shown in *Figure 9*. Occasional plateaus of this type are very much expected in a warming world, and decade-long pauses in warming can occur in the long-term rising temperature trend (Easterling and Wehner, 2009). A range of human and natural factors can influence air temperature in the shorter term, masking longer term trends related to a warming climate (*Box 2*).

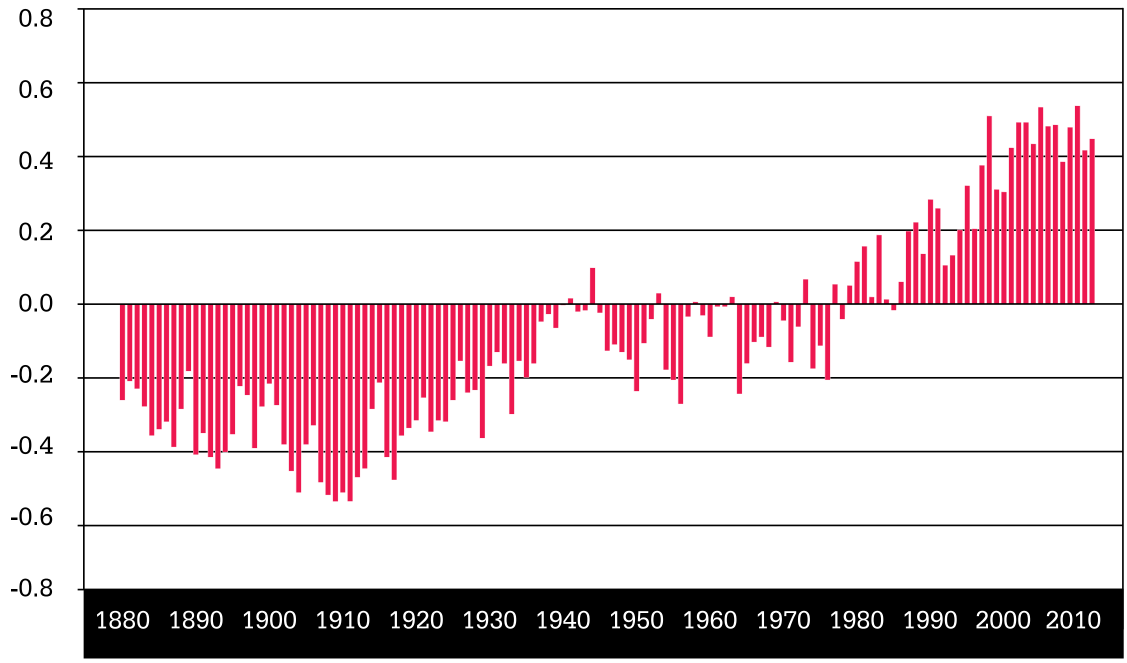
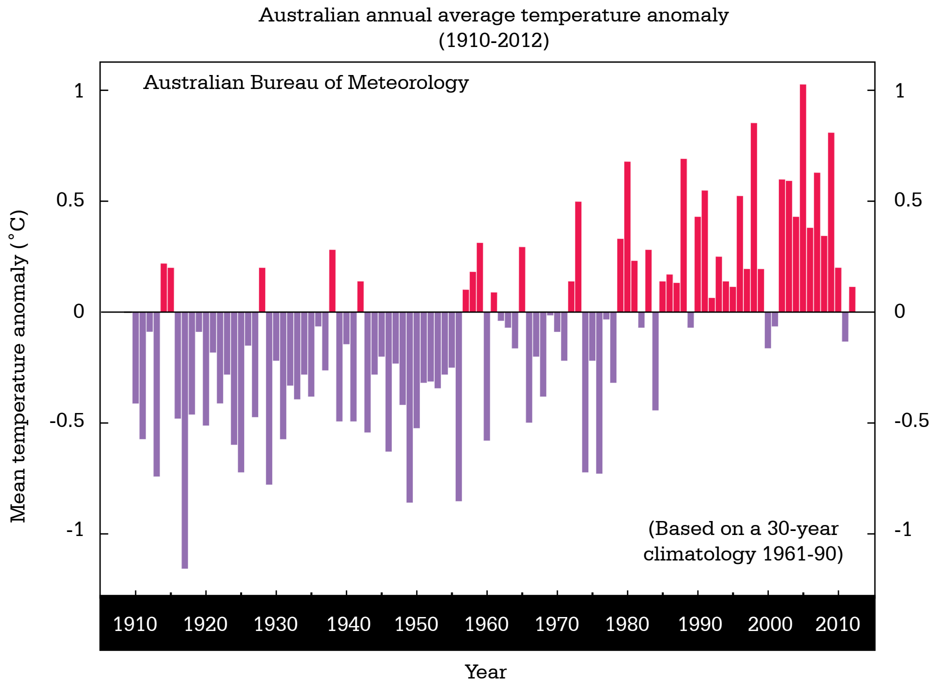



**Figure 9:** Global surface air temperature from 1880 through 2012.

**Source:** Produced by BoM for this report

THE EARTH IS WARMING STRONGLY AND HUMAN ACTIVITIES, THE BURNING OF FOSSIL FUELS AND DEFORESTATION, ARE THE PRIMARY CAUSE.

(a)




(b)

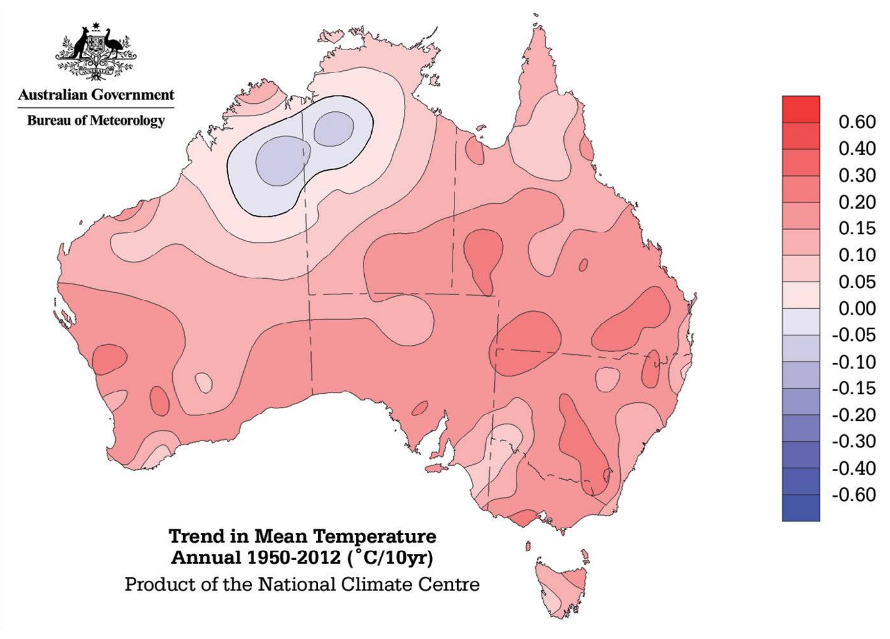



**Figure 10:** (a) The time series of the annual average temperature anomaly for Australia from 1910 through 2012, and (b) the trend in average annual temperature for Australia from 1950 through 2012.

**Source:** BoM, 2013b

### Box 2: Surface air temperature

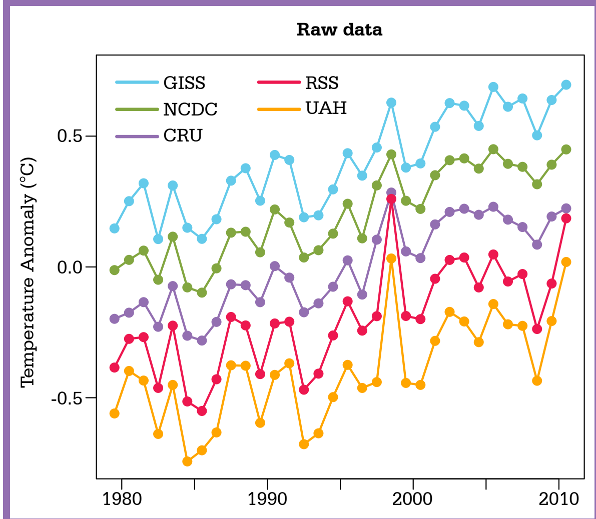
Many factors have influenced the observed surface air temperature trend over the past half-century in addition to the increase in greenhouse gases in the atmosphere. Some of these factors also arise from human activities, such as the emission of aerosols to the lower atmosphere and changes in land cover (*Figure 7*). Other factors are types of natural variability, such as variations in the intensity of incoming solar radiation, the injection of aerosols into the upper atmosphere by large volcanoes, and changes in the exchange of heat between the air and the ocean through phenomena such as the El Niño Southern Oscillation (ENSO) (see *Box 4*). Over short periods of time, such as a few years or a decade or two, combinations of these natural factors can mask the long-term, underlying trend of rising temperature due to greenhouse gas increases.

An evaluation of these factors over the last three decades shows how this masking effect can occur. *Figure 11* shows the raw temperature data for the 1979-2012 period, the end of the long-term air temperature record. The plateau is clearly visible.

Over the 1979-2010 period the changes in solar intensity have been measured, and the timing and aerosol emissions of large volcanoes like Mount Pinatubo are also known. In addition, much has been learned about the effects of ENSO on global average temperature, as shown in *Figure 12* where the La Niña years, for example, are cooler than the average. The magnitude of this cooling effect, and the corresponding warming effect when an El Niño event occurs, can also be measured.

All three of these natural factors – solar intensity, volcanoes and ENSO – can then be applied to adjust the observed temperature trend from 1979 to 2010 (Foster and Rahmstorf, 2011). If the underlying warming trend due to increasing greenhouse gases had paused, the temperature plateau would remain. Conversely, if the underlying trend was continuing but being masked over the last decade or so by natural variability, the trend should reappear when the effects of natural variability are removed. The answer is shown in *Figure 13*. When the temperature data are adjusted to remove the estimated impact of the known factors on short-term temperature variations, the global warming signal becomes clear. The underlying greenhouse gas-driven warming trend continues unabated; it has simply been masked by the shorter-term effects of natural variability.

Furthermore, there is no plateau in ocean heat content, which accounts for about 90% of the additional heat trapped by the increasing concentration of greenhouse gases in the atmosphere (*Figure 8*). Warming of the ocean continued unabated over the last 10-15 years.



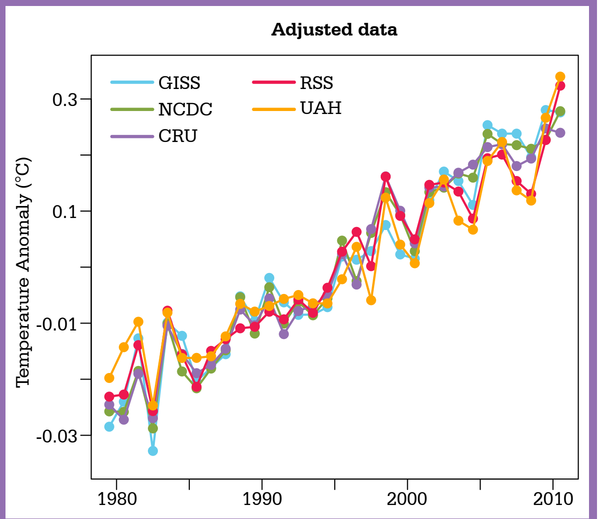




**Figure 11:** Five major global surface air temperature records for the period 1979 through 2012.

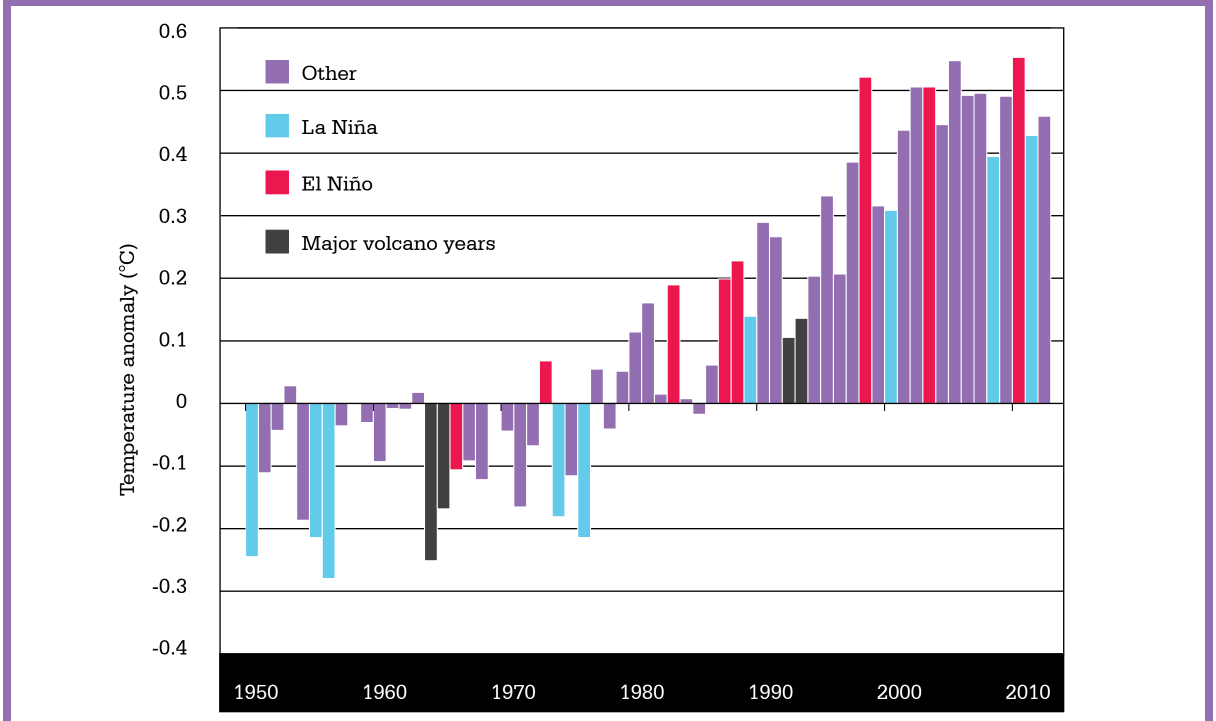
**Source:** Foster and Rahmstorf, 2011

**Figure 12 (below):** Time series of global surface air temperature anomaly with El Niño, La Niña and major volcano years highlighted.

**Source:** Produced by BoM for this report

**Figure 13:** Temperature data from different sources (GISS: NASA Goddard Institute for Space Studies GISS; NCDC: NOAA National Climate Data Center; CRU: Hadley Centre/ Climate Research Unit UK; RSS: data from Remote Sensing Systems; UAH: University of Alabama at Huntsville) corrected for short-term temperature variability. Compare this corrected trend line with the uncorrected trend line in *Figure 11*.

**Source:** Foster and Rahmstorf, 2011



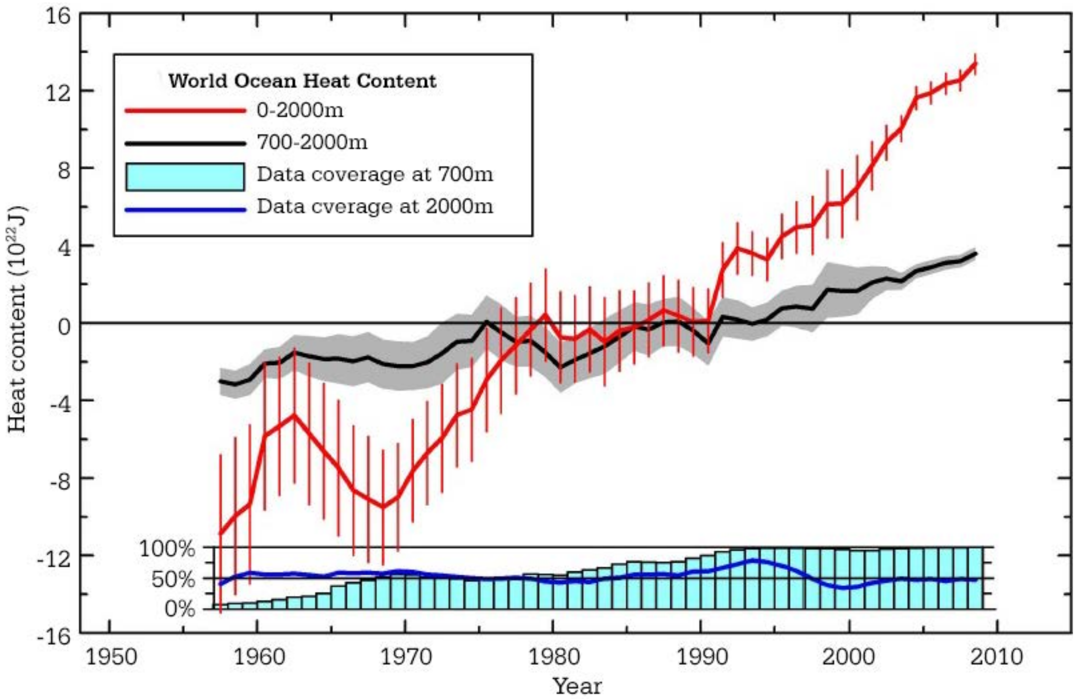



**Figure 14:** Time series of global ocean heat content demonstrating an increase in heat content (measured as $10^{22}$ J) for both the 0-2,000 m and 700-2,000 m layers of the ocean since 1955. The red line demonstrates the 0-2,000 m layer and the black line demonstrates the 700-2000 m layer. Measurements are based on running averages over five-year periods, relative to 1955-2006. The vertical red bars represent +/- 2 times the standard error of the mean 0-2,000 m estimates and the grey-shaded area represents +/- 2 times the standard error about the 700-2,000 m estimates. The blue bar chart at the bottom represents the percentage of one-degree squares (globally) that have at least four 5-year one-degree square anomaly values used in their computation at 700 m depth. Blue line is the same as for the bar chart but for 2,000 m depth.

**Source:** Levitus et al., 2012

## Ocean heat content

As noted in *Section 1* (*Figure 8*) nearly 90% of the excess heat in the climate system is stoed in the ocean. Ocean heat content has been increasing steadily since 1955 (Levitus et al., 2012; *Figure 14*). The surface waters of the ocean have warmed over the 20th century and continue to warm; on average the temperature of the 0-700 m layer has increased by 0.18°C between 1955 and 2010 (Levitus et al., 2012). Substantial warming has occurred in the oceans surrounding Australia (CSIRO and BoM, 2007; *Figure 15*). A feature of the South Pacific, near the east coast of Australia, is a large warming associated with changes in the East Australian Current. In the Indian Ocean, warming along the Western Australian coast is greater than that further offshore.

While most of the warming of the ocean has occurred in the surface waters (0-700 m), about 30% of warming in the last decade has occurred at greater depths, between 700 and 2,000 m (Balmaseda et al., 2013). This extra heat has contributed to the increased rate of warming of the ocean (Balmaseda et al., 2013). The 0-2,000 m layer as a whole has experienced an average increase in temperature of 0.09°C between 1955 and 2010 (Levitus et al., 2012).

While this increase may seem minor, a small change in the ocean temperature requires a massive amount of heat compared to that required to warm the atmosphere. For example, warming the whole atmosphere by 1°C requires the same amount of energy as heating just the top 3 metres of the ocean by 1°C (ACE CRC, 2011).

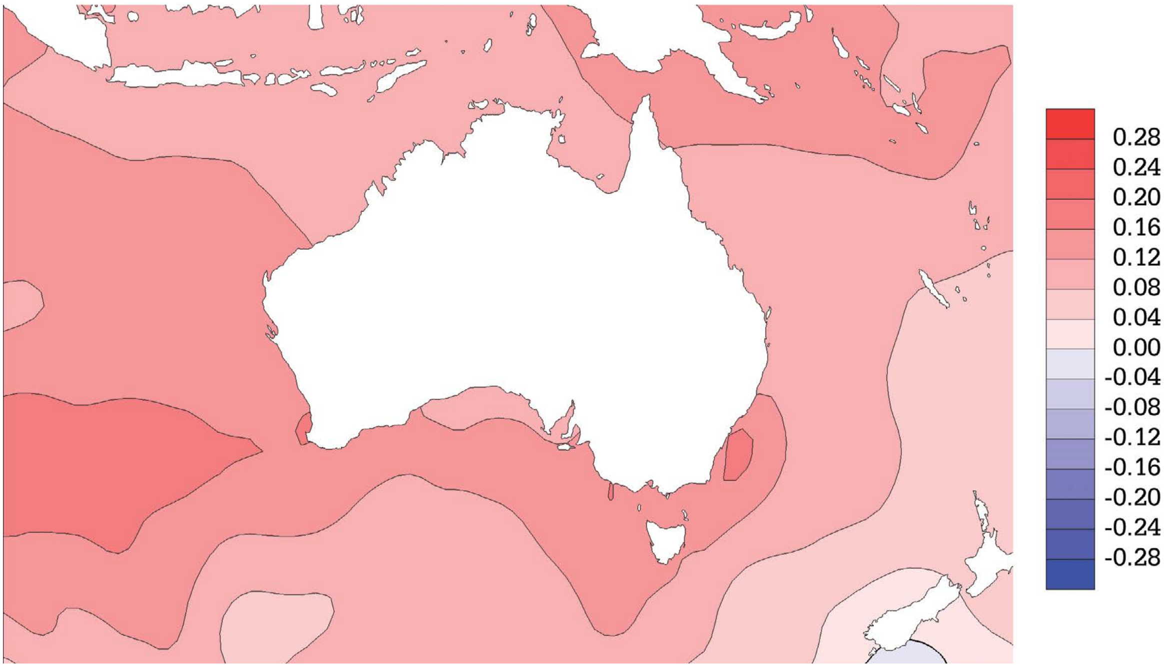



**Figure 15:** Trend in annual sea surface temperature for the Australian region, 1950-2012 (°C/10 yr).

**Source:** Produced by BoM for this report

## Rainfall

Global precipitation patterns are changing, with some notable trends being observed. Significant increases in precipitation have occurred in the 1900-2005 period in northern Europe, over northern and central Asia and over the eastern parts of North and South America. Drying trends have been observed in the Mediterranean region, the Sahel, southern Africa and over parts of southern Asia (IPCC, 2007). However, it is difficult to determine an overall global trend in precipitation because rainfall and snow are highly variable in time and space and there is a lack of data for many regions of the world.

In Australia, some pronounced regional rainfall trends have emerged since 1970, the period during which rising temperature due to increasing greenhouse gas concentrations has become most evident. In particular, the southwest corner of Western Australia and the far southeast of the continent, along with Tasmania, have become drier (*Figure 16b*). Less significant drying trends have also been observed along much of the east coast and in the centre of the continent.

Overall, annual rainfall increased slightly across most of the country between 1900 and 2012 (*Figure 16a*). The simple linear trend, however, masks significant decade-to-decade variability in many regions of Australia. In drier parts of the country, changes to decadal variability, such as the frequency of droughts and wet periods, can have profound influences on soil moisture, stream flow and evaporation rates.

In southwest Western Australia, annual average rainfall has declined since the late 1960s, with reductions becoming greater and more widespread since 2000 (IOCI, 2012). The largest reductions have been observed in autumn and winter, when most rainfall occurs. These observed changes have been linked with large-scale atmospheric changes (IOCI, 2012). The causes of the rainfall changes are broadly consistent with human-induced forcing, but uncertainties remain relating to why the changes have occurred

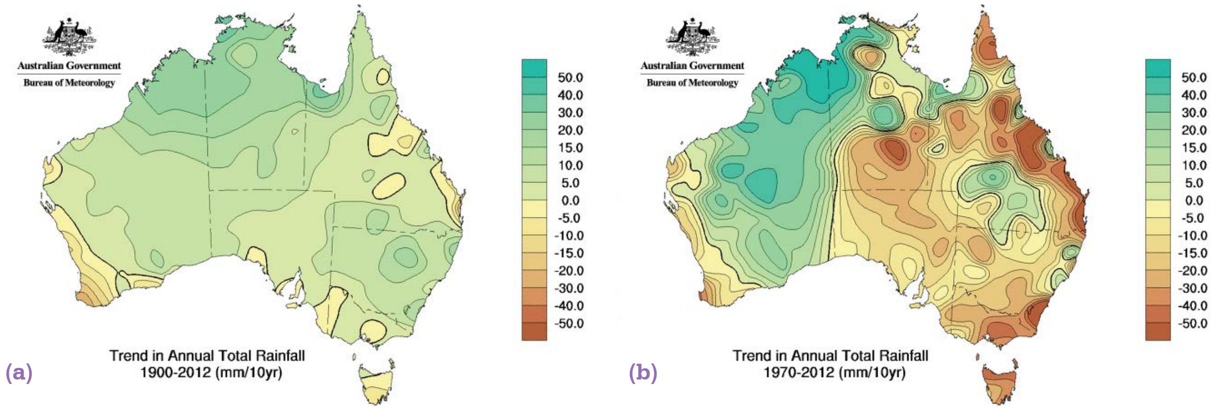



**Figure 16:** Trend in annual rainfall across Australia for the periods 1900-2012 (a) and 1970-2012 (b).

**Source:** BoM, 2013c

in particular seasons, and why the observed drying has been larger than that simulated in climate models. This remains an active area of research (Timbal et al., 2010).

Although very wet conditions associated with the La Niña events of 2010-11 and 2011-12 occurred across much of Australia, with some devastating extreme events such as the Queensland floods, the longer-term regional drying trends over the southeast continued. During the cooler months, and especially late autumn and early winter, rainfall has been below average across many areas of southern Australia (BoM, 2013d).

## The Cryosphere – Ice and snow

The cryosphere is comprised of parts of the Earth system that are subject to temperatures below 0°C for at least part of the year. Its largest components are the ice sheets in Greenland and Antarctica, but it also includes:

- Ice caps and glaciers on continents
- Sea ice
- Ice shelves
- Snow
- River and lake ice
- Frozen ground (permafrost).

The cryosphere plays an important role in moderating the climate system. Snow and ice reflect a very high percentage of the radiation received by the sun, helping to regulate Earth's temperature. The cryosphere contains nearly 75% of the Earth's fresh water (NASA, 2013).

**Ice sheets:** The change in the ice mass of the large polar ice sheets on Greenland and Antarctica is of considerable interest, both as an indicator of a changing climate and as a contributor to sea-level rise (see next section). A warming climate system drives loss of ice from the polar ice sheet by two processes – melting at the surface of the ice sheet (*Figure 17*) and dynamic ice processes, the transport of solid ice to the sea before it melts. The latter process can be quite spectacular, with the calving of very large pieces of ice from the terminus of land-based ice sheets.

Over the past two decades both of these processes have been observed on the Greenland and Antarctic ice sheets; they are experiencing a combined net loss of ice (Shepherd et al., 2012; Rignot et al., 2011; *Figure 18*). The mass of these ice sheets has changed from being in balance (no net gain or loss of ice) in the early 1990s to an average net loss of about 600 billion tonnes per year by the 2008-2010 period. The loss of ice is accelerating, that is, the rate at which ice

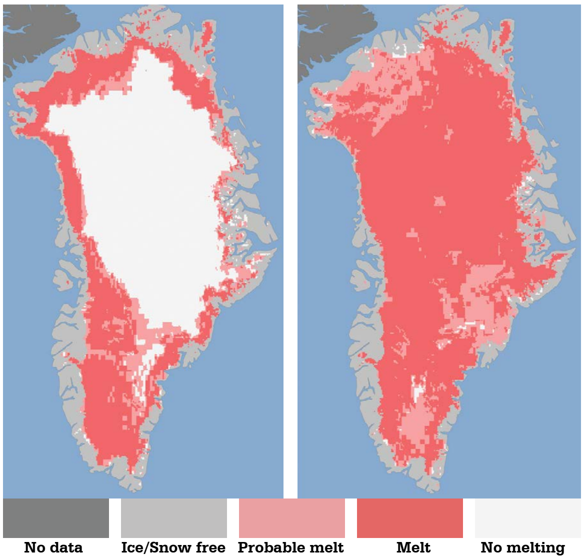



**Figure 17:** NASA satellite image of the extent of surface melt over Greenland's ice sheet on 8 July 2012 (left) and 12 July 2012 (right).

**Source:** NASA, 2012

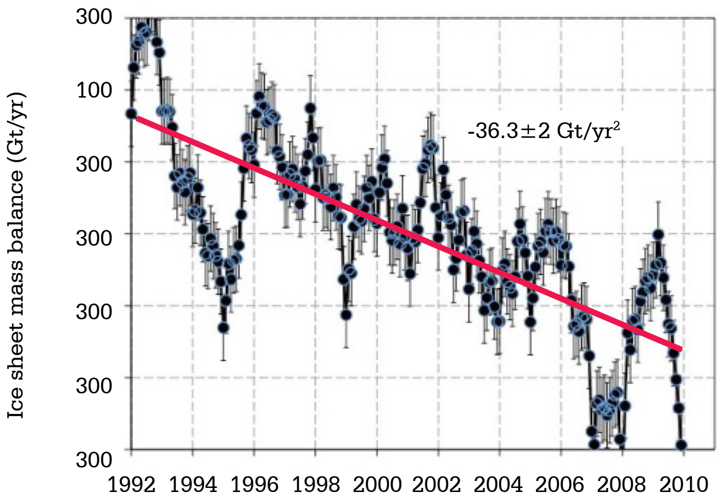



**Figure 18:** Trend in ice loss (land-based ice sheets) from Greenland and Antarctica combined between 1992 and 2010.

**Source:** Rignot et al., 2011

is being lost from year-to-year is increasing by an additional 36 billion tonnes per year (Rignot et al., 2011).

**Sea ice:** Changes in sea ice – the thin layers of ice floating on the surface of the Arctic Ocean and around Antarctica – are also indicators of changes in the state of the climate system. The area of Arctic sea ice has seen a dramatic downward trend for several decades, particularly over summer, with a record low set during the northern hemisphere summer of 2012 (*Figure 19*). The average rate of decrease in summer ice extent has been 11% per decade since 1979 (Stroeve et al., 2007). This is consistent with the strong regional warming in the northern high latitudes and is probably amplifying the regional warming by decreasing the reflection of sunlight as the ice disappears (*Box 1*).

The sea ice around Antarctica, on the other hand, has experienced a slight increase in extent over the period since 1979 but with large regional variations linked to changes in both temperature and atmospheric circulation (Comiso and Nishio, 2008; Turner et al., 2009).

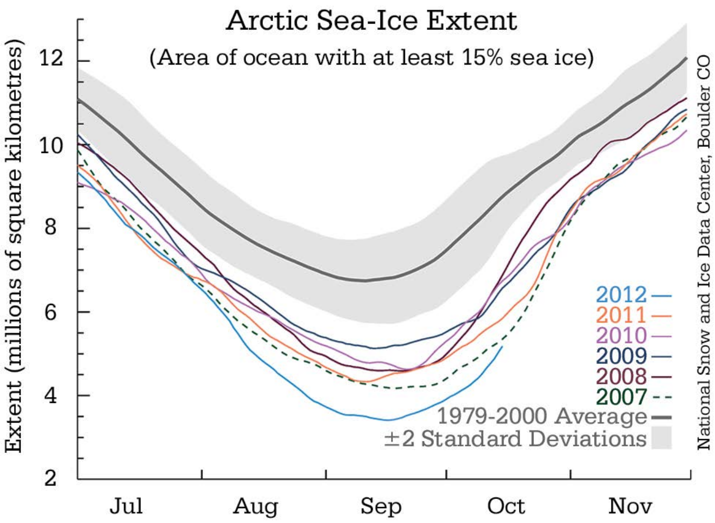



**Figure 19:** Trend in the Arctic sea-ice extent from 1979 through 2012. Each line represents an annual cycle with the lowest sea ice extent occurring at the end of the northern hemisphere summer. A record of low summertime ice extent was set in 2012.

**Source:** National Snow and Ice Data Center, Boulder, CO, USA

In particular, sea ice has melted back significantly around the Antarctic Peninsula and near the West Antarctic Ice Sheet, whereas sea ice has expanded around the Ross Sea (ACE CRC, 2009). The Ross Sea expansion in sea ice has been linked to fresher ocean conditions there due to increased ice-shelf melt in the region (Bintanja et al., 2013).

**Snow:** Snow cover has decreased in most regions around the world, especially in the northern hemisphere spring (IPCC, 2007). This is most pronounced in the northern hemisphere, where snow cover decreased in every month except November and December over the period 1966 to 2005, with a stepwise drop of around 5% in the annual average in the late 1980s (IPCC, 2007). Decreases in mountain snowpack, as measured by time series of snow water equivalent and snow depth, have been observed in many mountainous regions around the world, such as western North America and the European Alps (IPCC, 2007).

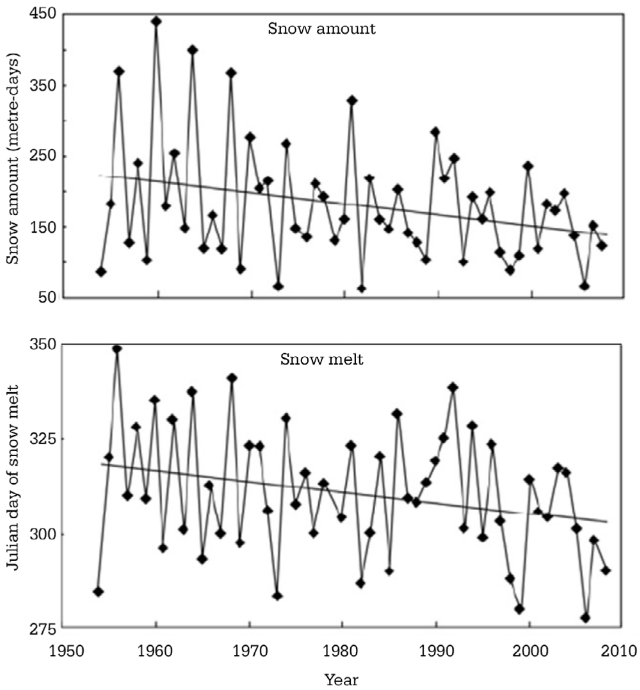



**Figure 20:** Trend in snow amount and date of snow melt at Spencers Creek, NSW alpine region, from 1954 to 2008.

**Source:** Green, 2010

The Australian Alps have also experienced a decrease in snow cover over the past half-century. Although there is much variability from year to year, the overall downward trend in snow depth in the Snowy Mountains is clear (*Figure 20*).

## Sea level

As expected with a warming climate, sea level is rising. Global average sea level has risen by 1.7 mm per year over the period 1900-2009; the average rate was about 3 mm per year for the last two decades (Church and White, 2011; *Figure 21*). In 2011 global average sea level was 201 mm (+/- 30 mm) above the level in 1880 (CSIRO and BoM, 2012).

Over 1933-2010, observed sea-level rise around the Australian coast shows significant variation from the global average, with the northern and western coasts experiencing higher-than-average rates of sea-level rise while the rates along the southern and eastern coasts are close to the global average (*Figure 22*). However, the regional data span only two decades, so the variability around the Australian coast could also have a temporal dimension due, for example, to trends in ENSO and other modes of natural variability (Church et al., 2011a; Hunter et al., 2013).

The factors that contribute to the rising sea level are becoming better understood (Church et al., 2011a;b). Over the 1972-2008 period, the most important contributor to sea-level rise was the expansion of the volume of ocean water. As the heat content of the ocean has increased the ocean has expanded, contributing around 0.8 mm per year of sea-level rise. The loss of mass of glaciers and ice caps in regions such as Alaska, the Andes and the Himalaya has also made an important contribution to sea-level rise, about 0.7 mm per year. Melting of the large polar ice sheets on Greenland and Antarctica contributed about 0.4 mm per year, although over the past two decades, the relative contribution of the polar ice sheets has increased such that this is now the major source (Shepherd et al., 2012).

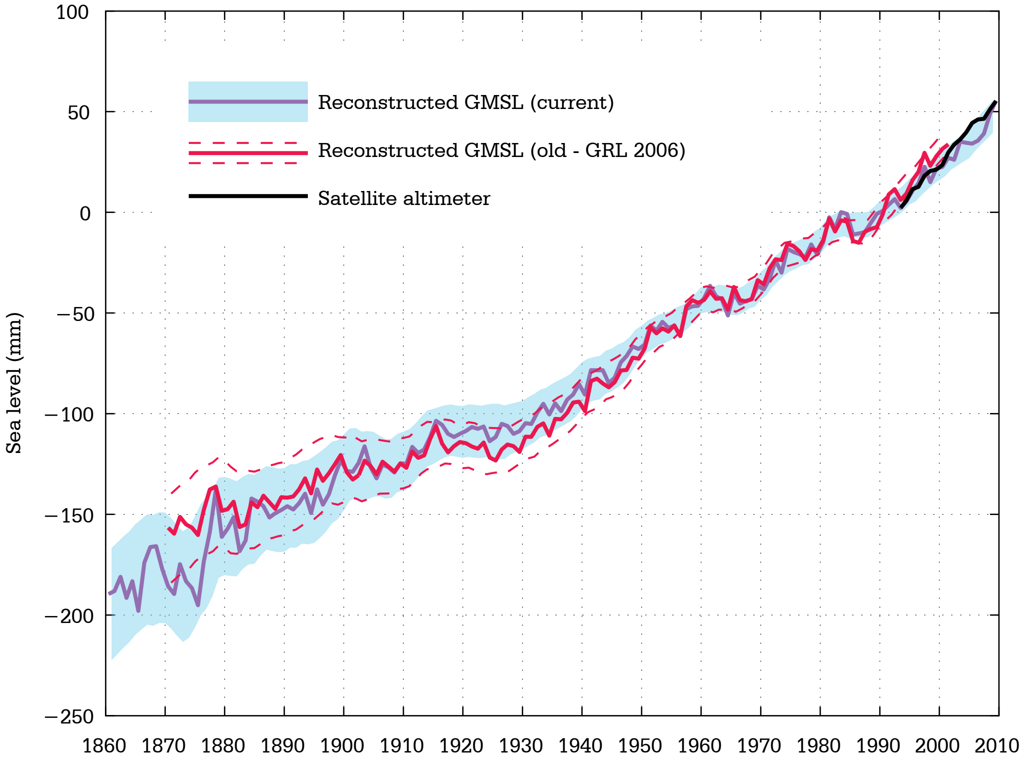



**Figure 21:** Increasing global average sea level from 1860 to 2009. Earlier estimates for 1870-2001 (Church and White, 2006) are shown by the solid red line. Satellite altimeter data since 1993 are shown in black (Church and White, 2011). Shading and dashed lines are one standard deviation error.

**Source:** Church and White, 2011

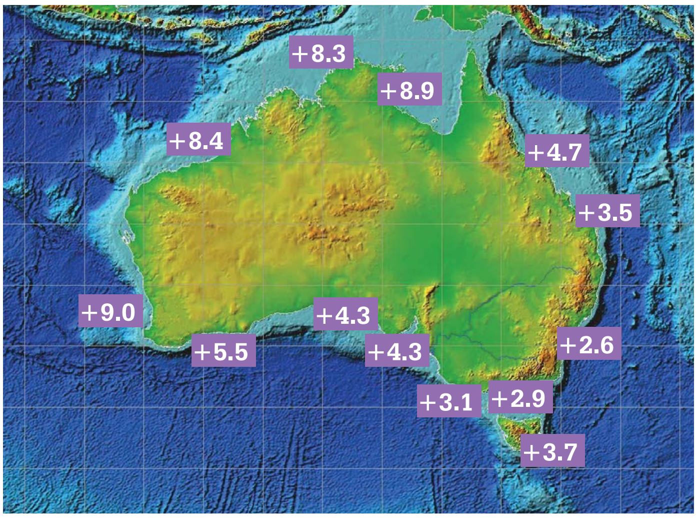



**Figure 22:** The regional variation of the rate of sea-level rise (mm per year) around Australia from the early 1990s to 2011.

**Source:** NTC, 2011

AS EXPECTED WITH A WARMING CLIMATE, SEA LEVEL IS RISING

## Ecosystems

Many plant and animal species are sensitive to the changes in climate that have already occurred over the past few decades. Changes in species distributions, life cycles, body size, and genetic makeup are consistent with what is expected from a warming climate (*Figure 23*).

As the climate warms, many species capable of dispersal are responding by moving to cooler places – either to higher latitudes or to higher elevations. This is particularly well documented in marine systems along Australia's east coast where fish and intertidal species are being increasingly observed at more southerly locations than in the past (Last et al., 2011; Pitt et al., 2010).

Some land species are also moving in response to the warming climate. On a global scale, large-scale compilations of observations have found that many terrestrial species had moved poleward by an average of 6.1 km/decade (Parmesan and Yohe, 2003) over the past few decades. More recent estimates, however, have found rates of range shift two to three times higher (16.9 km/decade) (Chen et al., 2011), suggesting that species shifts may be accelerating.

The life cycles of many species are attuned to temperature – as the temperature increases in spring, many important events such as reproduction and migration are triggered.

As average temperatures increase, these events are often occurring earlier in the year. While there is considerable variability in responses among species, and among different regions, some of the significant changes in life cycles include earlier arrival and later departure of migratory birds (Beaumont et al., 2006; Chambers, 2008), earlier emergence of

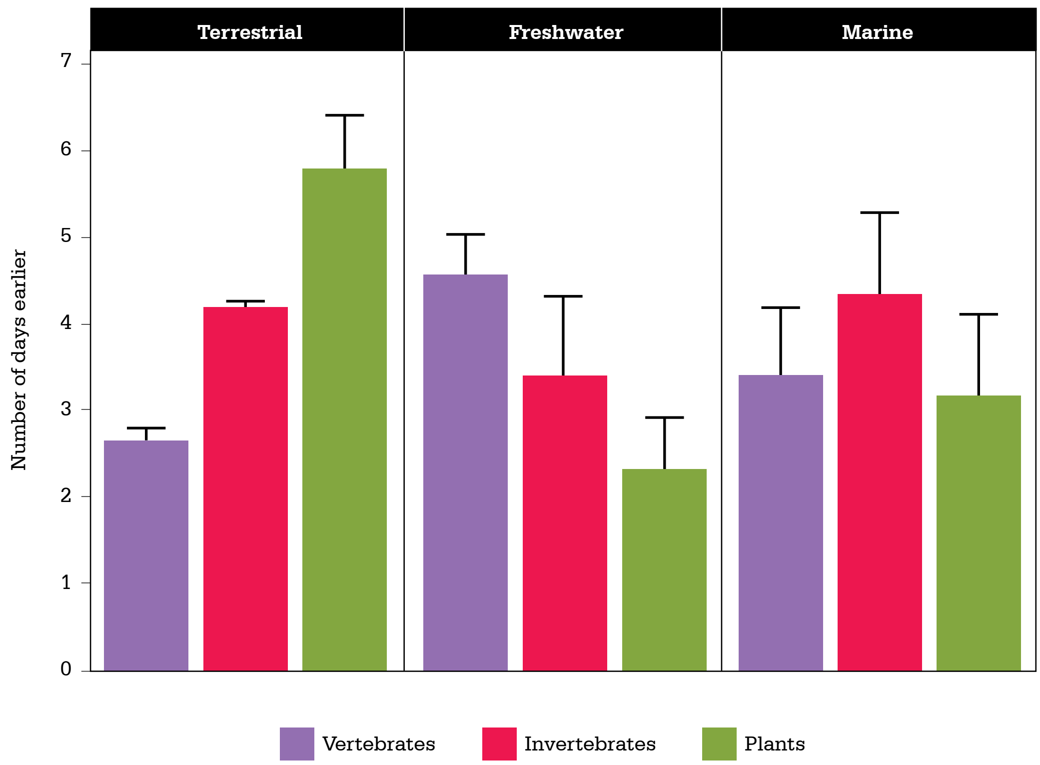



**Figure 23:** Changes in the timing of life cycles in plants and animals in the United Kingdom (1976-2005). Life cycles of plants, invertebrates and vertebrates are consistently advancing in marine, freshwater and terrestrial systems.

**Source:** Redrawn from Thackeray et al., 2010

butterflies (Kearney et al., 2010), earlier plant flowering times (Rumpff et al. 2010) and earlier mating and reproduction (Bull and Burzacott, 2006; Telemeco et al., 2009; Gibbs et al., 2011).

Small organisms with rapid life cycles may be able to adapt genetically to a rapidly changing climate. In eastern Australia, an increased frequency of heat-tolerant genotypes has developed among southern populations of fruit flies since the early 1980s (Umina et al., 2005). These populations now have the genetic constitution of more northerly populations, equivalent to a four-degree shift in latitude.

Climate change may even be affecting the size of individual plants and animals. In warmer climates, species naturally tend to be smaller because higher surface area-to-volume ratios maximise heat loss. There is evidence that this effect may already be occurring in response to a warming climate in birds (Gardner et al., 2009) and plants (Guerin et al., 2012).

Gradually increasing sea surface temperatures over the past few decades have been associated with declines in the growth rate and biomass of the spring phytoplankton bloom in the western Tasman Sea (Thompson et al., 2009), emergence and increased incidence of coral diseases including white syndrome (since 1998) and black band disease (since 1993-4) (Bruno et al., 2007; Sato et al., 2009; Dalton et al., 2010), and with declining calcification rates of *Porites* coral on the Great Barrier Reef, although increasing ocean acidity may also be contributing to this trend (Cooper et al., 2008; De'ath et al., 2009).

Impacts of climate change at an ecological community level are difficult to separate out from other environmental changes. However, it is likely that elevated atmospheric $CO_2$, in combination with changes in fire and rainfall patterns, has affected the density of woody plant species in savannas (Fensham et al., 2005), and has altered the boundaries between different vegetation types such as those between savannas and monsoon rainforests in northern Australia (Bowman et al., 2010), and between wetlands and eucalypt woodlands in the southeast (Keith et al., 2010). As some species adapt more quickly to the changing climate, the relative proportion of different types of species in ecological communities will change. This is already being seen in freshwater communities, where invertebrates that favour warmer waters are becoming more prevalent, relative to those that favour cooler temperatures (Chessman, 2009).

## 2.2 Projections of future change

### Temperature

Global average surface air temperature is projected to continue to rise during the 21st century (IPCC, 2007). By 2030 this increase is projected to be between 0.64°C and 0.69°C, compared to 1980-1999 levels (IPCC, 2007). Note that the 1980-1999 average temperature is already about 0.5°C above the pre-industrial level. These medium-term projections are little affected by different scenarios of levels of future greenhouse gas emissions because approximately half of this warming is already committed due to lags in the climate system (IPCC, 2007).

Further into the future, the level of emissions we produce in the next decade and beyond will strongly influence the amount of warming. The IPCC (2007) reported that by 2100, temperatures are expected to rise between 2.0°C and 6.2°C, relative to 1980-1999 levels, depending on the amount of emissions released and the sensitivity of the climate system to the amount of greenhouse gases emitted. Newly developed emission scenarios, called Representative Concentration Pathways (RCPs), which will be used to inform the IPCC Fifth Assessment Report's projections, indicate average temperature increases of between 1.3 and 6.1°C by 2100 (Rogelj et al., 2012).

Warming is expected to be greatest over land (roughly twice the global average temperature increase) and at high northern latitudes (IPCC, 2007). Less warming is expected over the southern oceans and the North Atlantic (IPCC, 2007).

The best estimate for average annual warming across Australia by 2030 (compared to 1980-1999) is about 1.0°C (CSIRO, 2011). Warming is expected to be stronger inland, about 1-1.2°C, and less in coastal areas, about 0.7-0.9°C (CSIRO, 2011).

## Sea-level rise

The IPCC (2007) found that sea level could rise by between 0.18 and 0.59 m, not including a rapid dynamic response of the ice sheets, by the last decade of the 21st century compared to the 1990 baseline. Depending on how large the rapid dynamic responses of the Greenland and Antarctic ice sheets are, sea level could rise an additional 0.1 to 0.2 m (IPCC, 2007; Church et al., 2011a; *Figure 24*).

The contribution from the dynamic response of the Greenland and Antarctic ice sheets was considered separately in sea-level rise projections in the IPCC Fourth Assessment Report because there was an inadequate basis in the scientific literature for making a rigorous assessment and thus there was a large uncertainty. Polar ice sheets contribute to sea-level rise by two processes: (1) changes in the surface mass balance (i.e. the difference between melting and subsequent runoff and accumulation) and (2) ice dynamics, where the solid ice from the ice sheet is transported into the ocean. Warming of the air and the ocean can erode the edges of the ice sheets, leading to accelerated flow of the grounded ice behind. In West Antarctica, where much of the ice sheet is grounded below sea level, warming ocean waters can cause erosion underneath the ice sheet as well as at its edges, potentially leading to more rapid rates of discharge of ice into the ocean and consequently more rapid rates of sea-level rise.

Observations over the past twenty years show an increasing contribution of the Greenland and Antarctic ice sheets to sea-level rise (Shepherd et al., 2012). For example, between 1992 and 2009, Greenland contributed 0.2 to 0.4 mm per year to sea-level rise (ACE CRC, 2012). This rate increased to 0.4 to 0.7 mm per year for the period 2002 to 2009 (ACE CRC, 2012).

Some analyses, based on simple, semi-empirical models that correlate observed sea-level rise with observed air temperature rise, suggest that a sea-level rise of over 1.0 m by 2100 compared to 1990 is possible (Rahmstorf, 2007; Rahmstorf et al., 2012). An analysis taking into account the dynamics of polar ice sheet loss estimates a most likely rise in sea level of 0.8 m by 2100 compared to 1990 (Pfeffer et al., 2008).

Thus, there remains considerable uncertainty about the magnitude of global average sea-level rise that will eventuate by the end of the century. In addition to the uncertainty around the behaviour of the polar ice sheets, a fundamental source of uncertainty is the rate at which greenhouse gases will be emitted by human activities through the rest of the century. Deep and rapid cuts in emissions – that is, strong mitigation efforts – would lead to levels of sea-level rise by 2100 at the lower end of the range of projections (*Figure 24*).

Sea-level rise varies across the globe due to ocean density and circulation changes, with interannual to multi-decadal variability superimposed on long-term trends. Over the past 20 years western Pacific sea level has risen significantly, while many parts of the eastern Pacific have actually seen a small decline in sea level (McGregor et al., 2012). This is largely related to trends in the tropical Pacific wind field over this period (McGregor et al., 2012). Despite regional variations in decade-to-decade sea-level rise such as this, 21st century ocean warming and land-ice melt will almost certainly lead to a rise in sea level in most regions of the ocean, although with variations in magnitude from region to region.

Sea level will continue to rise for many centuries beyond the end of 2100, even if warming is kept below 2°C, owing to thermal inertia in both the oceans and the large polar ice sheets (Meehl et al., 2012). Enough land-based ice is contained in the Greenland and West Antarctic ice sheets to raise global sea level by about 7 and 5 m respectively, should both ice sheets disappear under strong and sustained warming scenarios (IPCC, 2007). In particular, such scenarios could lead to the crossing of a threshold for the Greenland ice sheet later this century, leading to the decay of much of the ice sheet (Lenton et al., 2008; Richardson et al., 2011; *Section 2.3*). Avoiding such thresholds is another strong argument for rapid and deep cuts in greenhouse gas emissions.

## Rainfall

The relationship between localised precipitation and atmospheric temperature trends is complex. As a consequence, it is difficult to make a definitive statement on the direction of precipitation trends at regional scales. However, a probability-based approach at a regional level can provide a likely range of expected changes for future precipitation.

Climate change can influence regional precipitation in a number of ways. A warmer atmosphere can hold more water vapour, and hence increase the likelihood of heavier precipitation events (*Figure 25*; see *Section 3.1: Heavy rainfall*). Changing atmospheric circulation also influences rainfall patterns (see *Section 3.1: Changes in the climate system that cause impacts: atmospheric circulation*).

In a warmer climate, it is expected that precipitation will generally increase in the tropics, decrease in the subtropics and increase at the poles (IPCC, 2007). This is because the poleward expansion of the Hadley circulation (the exchange of air from the tropics to mid-latitudes), together with a poleward migration of the mid-latitude jets

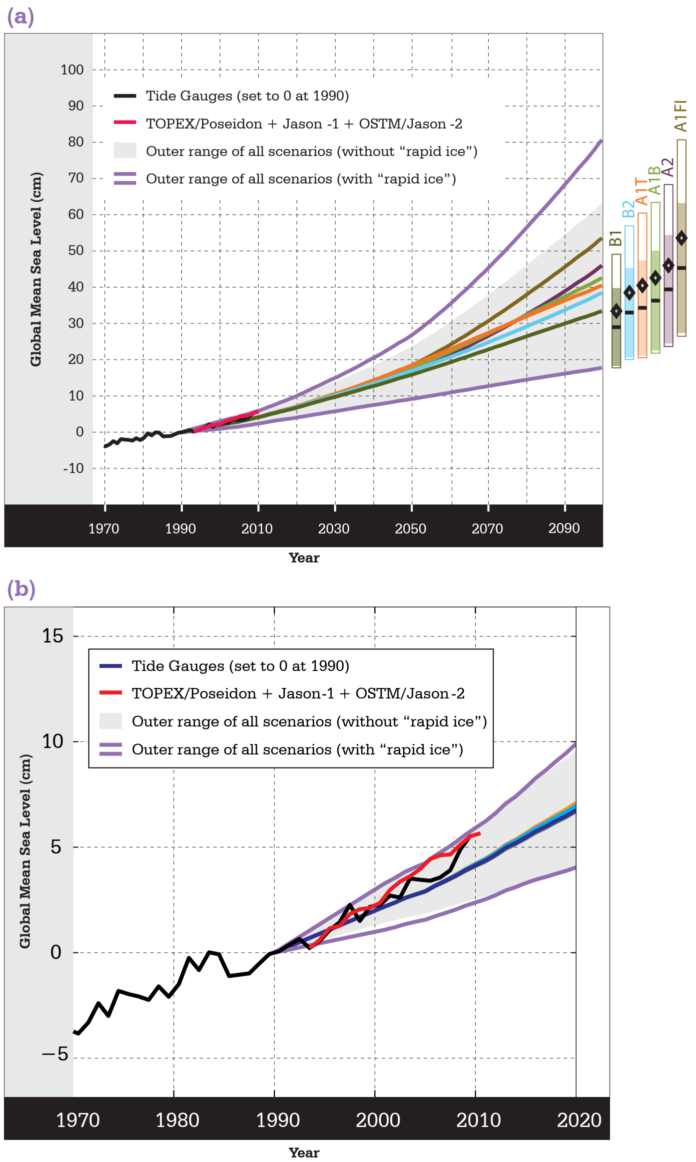



**Figure 24:** Global averaged projections of sea-level rise in the IPCC Special Report on Emissions Scenarios (SRES) to (a) 2100 and (b) 2020 with respect to 1990. The shaded region/outer light lines show the full range of projections, both those including and those not including any rapid ice component. The continuous coloured lines from 1990 to 2100 indicate the central value of the projections, including the rapid ice contribution. The bars at the right show the range of projections for 2100 for the various SRES scenarios. The horizontal lines/diamonds in the bars are the central values with and without the rapid ice sheet contribution. The observational estimates of global averaged sea level based on tide gauge measurements and satellite altimeter data are shown in black and red, respectively. The tide-gauge data are set to zero at the start of the projections in 1990, and the altimeter data are set equal to the tide-gauge data at the start of the record in 1993. The projections are based on the IPCC Fourth Assessment Report.

**Source:** Church et al., 2011a

(fast-flowing narrow air currents found at the mid-latitudes), is expected to generally decrease precipitation in the subtropics (IPCC, 2007).

On average, drier regions have been observed to become drier, while wetter regions have become wetter in response to warming, a broad pattern that is expected to continue as the climate warms further (Durack et al., 2012).

In Australia, while rainfall patterns are changing, there remain uncertainties about future changes, including the direction (increase or decrease) and the amount and seasonality of rainfall. For some locations, some climate models suggest lower rainfall in future while other models indicate higher rainfall. However, recent analyses have improved our understanding of how rainfall could change, particularly over southwest Western Australia and southeast Australia. For example, it is likely that southern Australia will experience a decrease in annual precipitation by 2030, especially in winter (CSIRO, 2012), and very likely that further decreases will occur over southwest Western Australia. Many estimates project little change in annual average precipitation over the far north of the continent, although an increase in summertime monsoon rainfall by the end of the century is projected by some models (Jourdain et al., 2013).

In southwest Western Australia, a reduction in winter and spring rainfall of around 10% is expected by 2030 (CSIRO and BoM, 2007), although much stronger declines have already been observed over the past four decades. Decreases in rainfall are projected for the months May to October in the future, with reductions potentially as large as, or larger than, those seen in the late 20th century (IOCI, 2012). In southeast Australia, there is less certainty about future changes, but new evidence suggests that the observed drying trend will continue, particularly in the cooler months (CSIRO, 2012).

### Ice and snow

Generally, as the climate warms, snow cover and sea ice extent are expected to decrease, and glaciers and ice caps are expected to lose mass (IPCC, 2007).

**Permafrost:** Further widespread increases in thaw depth over much of the permafrost regions are projected to occur in response to warming over the next century, possibly amplifying warming further. Under strong warming scenarios, thawing permafrost could emit 30-63 billion tonnes of carbon ($CO_2$ equivalent) by 2040 and 232-380 billion tonnes by 2100 (Schuur et al., 2011).

**Ice sheets:** Both the Greenland and Antarctic ice sheets are expected to continue to lose mass and contribute to sea-level rise throughout the 21st century by surface melt and dynamic loss of ice to the ocean. As discussed above, projections of the extent of ice sheet loss remain uncertain due to limited understanding of future dynamic ice-sheet responses.

A consistent feature of all climate models (see *Box 3*) is that projected 21st century warming is amplified in northern high latitudes including the Arctic Ocean and adjacent regions. This suggests continued melting of the Greenland Ice Sheet, with summer melting expected to continue to dominate over increased winter snowfall (IPCC, 2007). It is possible that the Greenland Ice Sheet will cross a threshold this century and will then be committed to largely disappearing, although it will take many centuries to millennia for this scenario to unfold (Lenton et al., 2008; Richardson et al., 2011; *Section 2.3*).

**Sea ice:** The IPCC (2007) projected a reduction in sea ice extent in the Arctic and Antarctic regions during the 21st century. A more recent analysis for the Arctic indicates larger reductions in sea ice extent than previously expected (Stroeve et al., 2012). However, melting of Arctic sea ice is outpacing even

these projections (*Figure 25*). A summertime ice-free Arctic within the next few decades is considered a distinct possibility (Wang and Overland, 2009; Stroeve et al., 2012).

In comparison to the Arctic, Antarctic sea ice is slightly increasing in some regions and decreasing in others. The predicted decline in Antarctic sea ice has only been observed to date around the Antarctic Peninsula, and of particular concern, near the West Antarctic Ice Sheet, where warming has been greater than over any other region of Antarctica (Steig et al., 2009). Increases in sea ice around certain areas of Antarctica are likely to be caused by accelerated melting of the ice shelves (Bintanja et al., 2013) and changes in local winds (Holland and Kwok, 2012). The IPCC (2007) estimates that by 2100 Antarctic sea ice will decline by 24% in annual average extent and 34% in annual average volume.

**Snow:** Snow cover is closely related to both temperature and the amount of precipitation. The IPCC (2007) estimates that there will be a widespread reduction in snow cover over the 21st century. However, there can be regional exceptions to this global trend, including in Siberia, where snow cover is expected to increase from autumn to winter (Meleshko et al., 2004; Hosaka et al., 2005 in IPCC, 2007).

In Australia the observed declines in snow cover are expected to continue. Under a best case scenario (least warming and most snowfall) areas with an average annual snow cover of at least 30 days per year could decline 14% by 2020 and 30% by 2050, relative to 1990 levels (Hennessy et al., 2008a). In business-as-usual scenarios (greatest warming and least snowfall) these losses could be as high as 54% by 2020 and 93% by 2050. The worst-case scenario is the complete loss of the alpine zone during this century (Hennessy et al., 2008a).

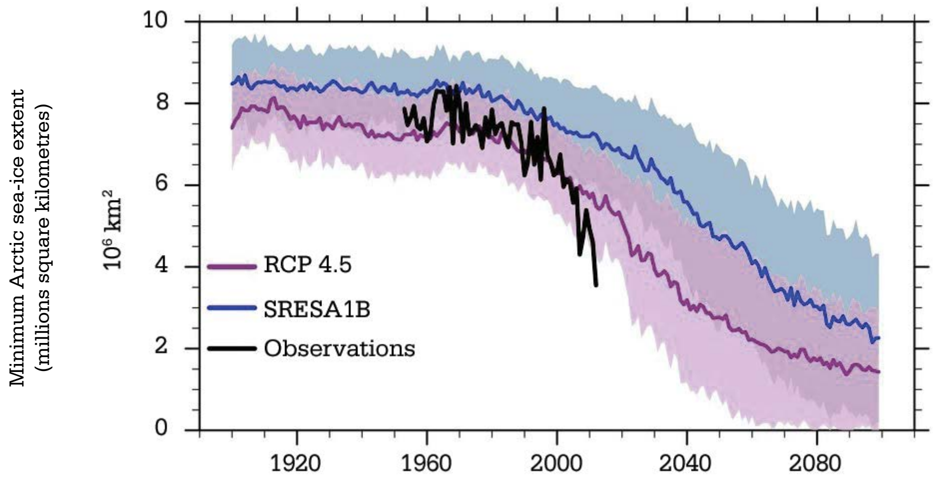



**Figure 25:** Observed and projected minimum Arctic sea-ice extent. The black line is the observed September Arctic sea-ice extent. The solid blue line shows the average of the CMIP3 SRESA1B (IPCC, 2007) projections and the solid red line shows the average of CMIP5 RCP4.5 projections. The shading represents one standard deviation around the two sets of projections.

**Source:** Stroeve et al. (2012) updated to include observations to 2012

**Box 3: How do climate models work?**

Climate models are mathematical representations of the climate system, expressed as computer code and requiring powerful computers to run because of the degree of detail in the model, the processes represented and the increasing level of spatial resolution. They are fundamentally based on established physical laws and tested with observations. State of the art Earth System models, such as the ACCESS (Australian Community Climate and Earth-System Simulator) model that has been developed by Australia's research community (CSIRO, Bureau of Meteorology and universities), are increasingly incorporating chemical and biological processes to evolve towards more complete representation of the whole climate system. Climate models incorporate the properties and interactions of the atmosphere, oceans, land and ice to simulate the climate dynamics of the past and present and make projections of future climate.

To project future climate, climate modellers use scenarios of future emissions of greenhouse gases as well as other substances that influence the climate, such as aerosols and ozone, as inputs to the models.

Climate variables, such as temperature and precipitation, are typically calculated in 15 to 30 minute time-steps across the Earth's surface and throughout the atmosphere and ocean, using a three-dimensional grid.

To provide a greater understanding of expected climate change at a more detailed level, regional climate models have been developed with much higher resolution, embedded within a global scale model. Regional climate models give a better representation of coastal and mountain effects and local-scale variations in climate, although they are ultimately constrained by the reliabiliity of the global-level climate projections on which they are based.

Confidence in model estimates is higher for some climate variables (for example, temperature) than for others (for example, precipitation). There is also greater confidence in large scale projections compared with projections at a regional level. Even with these limitations, climate models are the best tools that we have for projecting future climate change and provide important insights into directions and likelihoods of change, essential information both for informing adaptation approaches and for informing the debate about what constitutes 'dangerous' climate change. Climate models are comprehensively tested against observational data (*Figure 26*), including data from geological periods very different from our current climate, and are continuously improving in their abililty to simulate current and past climates, building more confidence in their projections of the future. Over several decades of climate model development they have consistently given a robust projection of significant temperature increases in response to greenhouse gas increases.

CLIMATE MODELS ARE THE BEST TOOLS THAT WE HAVE FOR PROJECTING FUTURE CLIMATE CHANGE

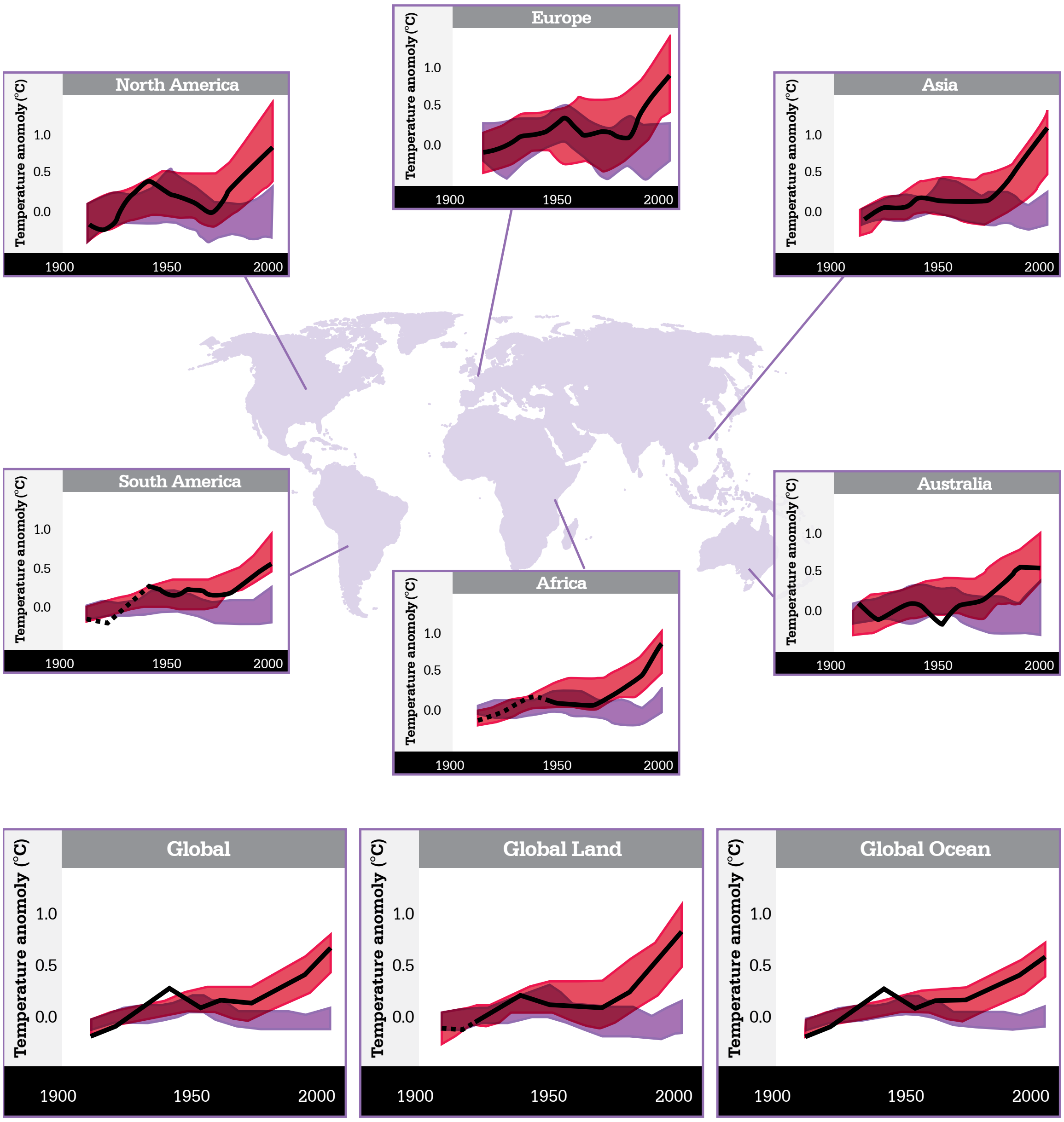



**Figure 26:** Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using only natural (purple shading) and the sum of human-induced plus natural forcings (red shading). Climate models capture the observed changes of the recent century of warming so long as human-induced greenhouse gas emissions are included. Natural forcings alone cannot account for the 20th century record. Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901 to 1950. Lines are dashed where spatial coverage is less than 50%. Purple shaded bands show the 5-95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5-95% range for 58 simulations from 14 climate models using both natural and human-induced forcings. This confirms that the recent warming observed over the Earth is caused primarily by human-induced greenhouse gas emissions, and not part of a natural cycle of warming.

**Source:** IPCC, 2007

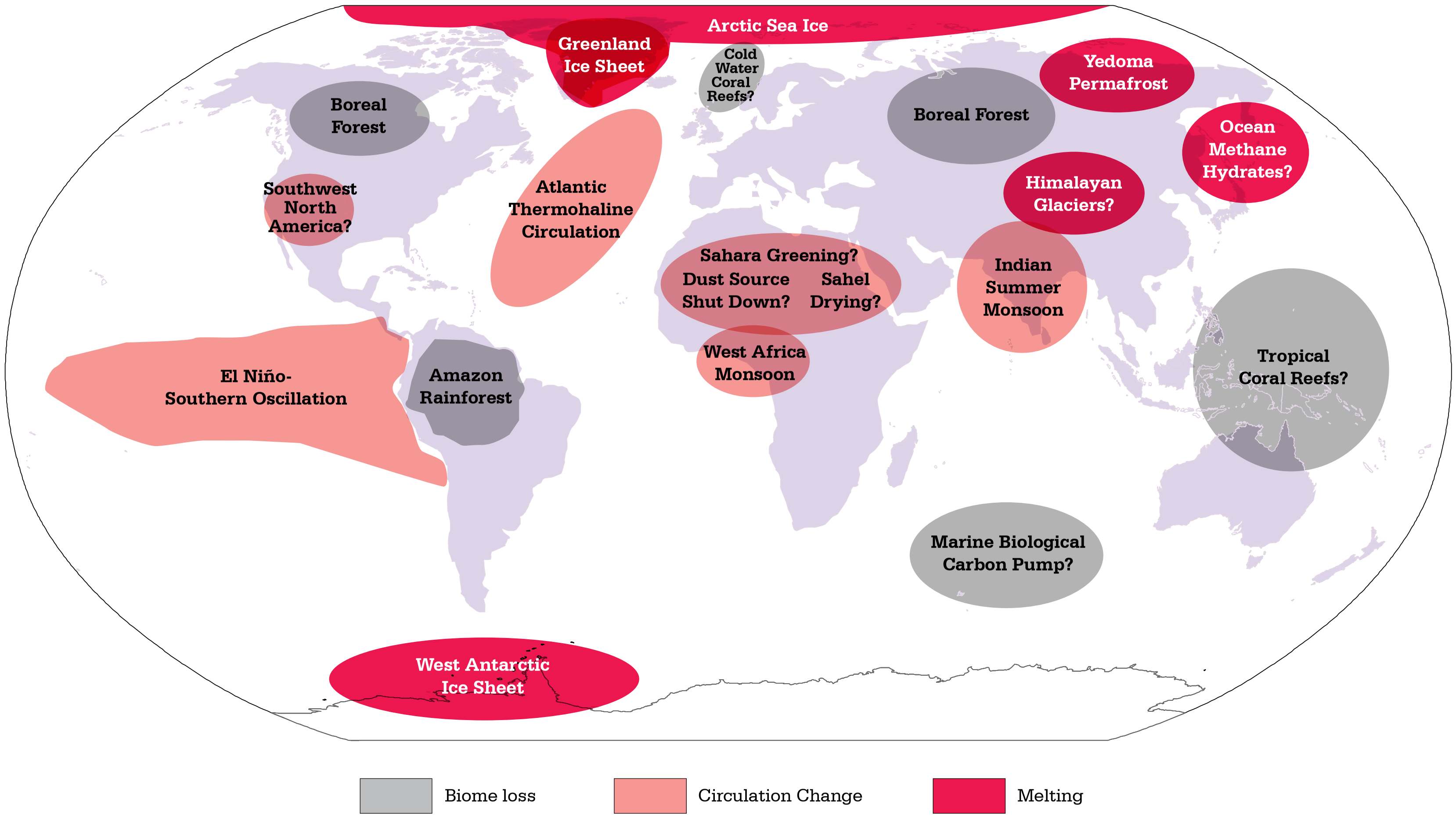



**Figure 27:** Map of potential tipping elements in the climate system that are relevant for climate policy. Question marks indicate systems whose status as policy-relevant tipping elements is particularly uncertain.

**Source:** Lenton et al., 2008, updated by further analysis by T.M. Lenton reported in Richardson et al., 2011

## 2.3 Abrupt changes: Tipping elements in the climate system

In many phenomena we experience in daily life, cause-effect processes occur where the size of the effect is proportional to the size of the cause. For example, the amount of water that comes out a tap (effect) is usually proportional to the amount that you turn the tap on (cause). Sometimes, however, we experience a quite different phenomenon in which the effect is somewhat disproportional to the cause; for example, an abrupt shift with just a small amount of additional forcing.

A classic example of an abrupt shift is tipping over a kayak. A kayak can exist in two stable states – upright and completely tipped over; it is not stable partially tipped over on its side. The kayak in its upright position is stable – up to a point. If you tip the kayak a little bit, it will return to the upright position. If you tip it a little more, it will still come back to the upright position. But if you tip it past a critical point – the threshold or so-called tipping point – the kayak will abruptly tip all the way over and leave you hanging upside down in the water. This is also a stable state, and it will take some effort and good technique to get the kayak upright again.

The same is true for the climate system. Many processes in the climate system show proportionality between the magnitude of the cause (forcing) and the magnitude of the effect (response). For example, the capacity of the air to hold water vapour increases in proportion to an increase in air temperature; and – measured over long enough periods of time – the global average temperature rises in proportion to the increase in radiative forcing.

However, there are other processes in the climate system, often called tipping elements, similar to that of a tipping kayak. These processes can respond slowly to an increasing amount of pressure up to a point – the threshold – after which they abruptly change state, just like a kayak tipping over when the threshold is crossed.

*Figure 27* shows a sample of such processes in the climate system that have shown tipping point behaviour in the past. They are surprisingly common, and encompass changes in atmospheric and ocean circulation, loss of ice, and changes in ecosystems. Examples of tipping points include melting of the Greenland Ice Sheet, a flip of the Indian summer monsoon to a drier state and a change of the Amazon rainforest to a drier biome such as a savanna.

Many of these processes can have direct impacts on human well-being. The Indian summer monsoon is an obvious one, as an abrupt shift to a drier state would endanger the production of food for over a billion people. The behaviour of the monsoon is related to the difference between the surface temperature of the Indian Ocean and the temperature over the land of the Indian subcontinent. The land-ocean temperature difference has a threshold, separating dry and wet states of the monsoon system. Both ocean and land temperature are being affected by human activities. The surface waters of the Indian Ocean are warming as part of the global trend of higher sea surface temperature, while the temperature over the subcontinent is being influenced both by climate change and by the presence of an 'atmospheric brown cloud' due to air pollution. The pollution scatters incoming sunlight and thus cools the surface, an effect opposite to that of greenhouse gases. Some models simulate a rapid change in the strength and location of the monsoon as a result of particular combinations of changes in these factors (Zickfield et al., 2005).

Other tipping elements with potentially serious consequences for human well-being are the large polar ice sheets on Greenland and West Antarctica. Although it would probably take many hundreds of years or even millennia for much of these ice sheets to be lost, thresholds for eventually losing all or most of the Greenland and West Antarctic ice sheets could be crossed this century under high warming scenarios (Lenton et al., 2008;

Richardson et al., 2011). That means that the decisions made during the next decade or two on the level of emission reductions could influence sea-level rise for hundreds of years.

The Greenland Ice Sheet, for example, is set to disintegrate once it melts below a critical threshold height. Beyond this threshold height the ambient air temperature is not cool enough to form snowflakes, and precipitation falls as rainwater rather than snow. The ice sheet then ceases to be regenerated at its highest altitude, and an irreversible melt is set to follow. Crossing ice-sheet thresholds would force future generations to live with a continuously rising sea level for many centuries or millennia, with rates of perhaps up to 1.0 m per century (Pfeffer et al., 2008; Stanford et al., 2011).

Other processes do not have direct impacts on human societies, but can have significant indirect impacts through the amplification of climate change. Examples include the loss of Arctic sea ice, which is already amplifying the regional temperature rise in the northern high latitudes, and outbursts of methane from clathrates (tiny cages of ice that trap methane within a crystalline lattice) under the continental shelves of some coastal seas and in the frozen soils in Siberia, northern Canada and Alaska.

Some recent sporadic release of methane, a potent greenhouse gas, has raised concern about the stability of the vast areas of frozen soil (permafrost; *Figure 28*) and lakes in the far north (Schuur et al., 2009; Walter et al., 2006). Over 1,600 billion tonnes of carbon are stored in the northern permafrost regions, about double the amount of carbon currently in the atmosphere (Tarnocai et al., 2009). This is an example of a positive feedback. As the Earth warms the permafrost melts, releasing methane or carbon dioxide. The greenhouse gases contribute to further warming, melting the permafrost and releasing even more methane or carbon dioxide (see *Section 2.2: Ice and snow*).

**Figure 28:** Permafrost in Spitzbergen, Norway. About 1,600 billion tonnes of carbon are stored in northern permafrost regions.

The location of the thresholds, in terms of the rise in global average temperature, for these tipping elements is obviously a critical question. While much remains to be learned about the probability of crossing thresholds for a given level of climate change, a thorough analysis in Lenton et al. (2008) and an update in Richardson et al. (2011) point to a 2°C temperature rise above pre-industrial as being especially important. While it is unlikely that the thresholds for the tipping elements in *Figure 27* lie below a 2°C rise, the risk of crossing many of these thresholds rises sharply above this level. This reinforces the urgency to reduce greenhouse gas emissions deeply so that the climate can be stabilised at a temperature no more than 2°C above the pre-industrial level.

## 2.4 Back to the future: Insights from past climate changes

The climate has changed naturally in the past at many different time scales, from decades and centuries to many millennia. Documenting and understanding these changes can give us many insights into the nature of contemporary climate change. Analysis of past climate changes can provide some clues as to the possible state of the climate system when it reaches equilibrium

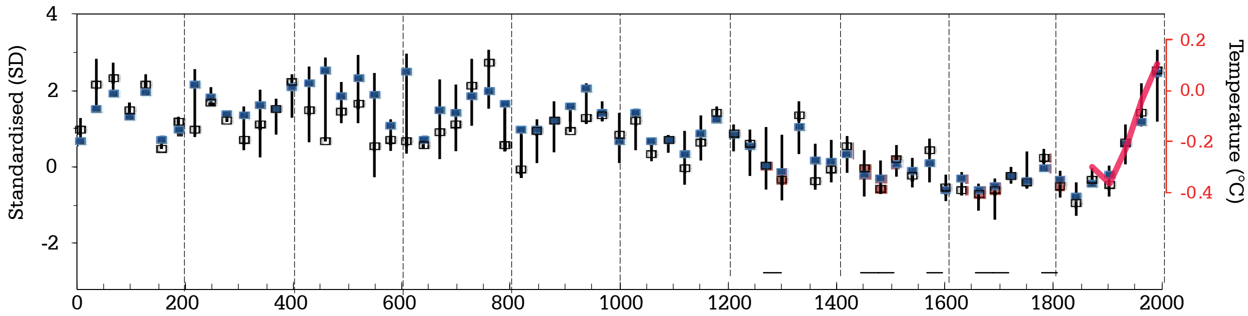



**Figure 29:** Standardised 30-year mean temperatures averaged across all seven continental-scale regions. Blue symbols are area-weighted averages and open black boxes are unweighted medians. The bars show the 25th and 75th unweighted percentiles to illustrate variability among regions. The red line at the right-hand end of the figure is the 30-year average annual global temperature from the HadCRUT4 instrumental time series relative to 1961-1990, scaled visually to match the standardized values over the instrumental period.

**Source:** Redrawn from PAGES 2k Consortium, 2013, which gives further information on the methodology used in the figure

following the current human-driven change. This is where greenhouse gas levels and global temperature reach a stable level. Information about the rate of change is more difficult, although some insights can be gained from the more recent past.

Examination of the temperature record over the past 2,000 years puts the climate changes of the last century, and particularly those since 1970, into a long-term context. Individual temperature records have been reconstructed for seven continental-scale regions for the past one to two thousand years (*Figure 29*) (PAGES 2k Consortium, 2013). This temperature record shows that the pronounced warming over the past century has reversed a long-term slow global cooling trend that had lasted for over a millennium. In fact, the most recent 30-year area-weighted reconstructed land temperature (for the period 1971-2000) was higher than for any other time in nearly 1,400 years. Furthermore, the work showed that the warming over land during medieval times (the so-called Medieval Warm Period) did not occur simultaneously around the globe. This is in sharp contrast to more recent warming, which has occurred globally (*Figure 26*). In summary, this record shows how unusual the past four decades of human-driven climate change is compared to the patterns of natural variability of the past 2,000 years (PAGES 2k Consortium, 2013).

Records from the past are consistent with the basic physics of the greenhouse effect. Estimates over the past 65 million years of temperature (Zachos et al., 2008) and atmospheric $CO_2$ concentration (T. Naish, pers. comm.) show a strong correlation; this covers a period from a much warmer, ice-free world in the distant past to the relatively cooler conditions of the more recent past. We can also learn much about the role of $CO_2$ by studying the cycle of ice ages and warmer interglacial periods of the last million years. Observations from Antarctic ice cores show a close connection between atmospheric $CO_2$ and warming during this period (Petit et al., 1999; Parrenin et al., 2013). While warming from the last ice age to the present interglacial period was triggered by changes in the Earth's orbit, and corresponding changes in solar radiation, data from the last 22,000 years shows that $CO_2$ emitted from warming oceans into the atmosphere played a strong amplifying role in further heating the climate system (Shakun et al., 2012). This is a clear demonstration of the important influence that $CO_2$ has on global temperature (IPCC, 2007).

Insights into contemporary climate change can be obtained by exploring the conditions during the last time on Earth when atmospheric concentrations of $CO_2$ were about 400 parts per million (ppm; see Glossary).

Those conditions occurred during the Pliocene, a warm period about 3-4 million years ago when the continents were also in approximately the same locations as they are today, and when the climate was in equilibrium with the atmospheric concentration of greenhouse gases. During the 400 ppm $CO_2$ world of the Pliocene, the global average temperature was about 2-3°C warmer than today, with greater warming in the northern high latitudes, similar to what is observed today (Naish and Zwartz, 2012). There is evidence of the periodic collapse of the West Antarctic Ice Sheet between 3.3 and 2.6 million years ago (McKay et al., 2012), and the Pliocene sea level was estimated to be 10-20 metres higher than today (Miller et al., 2012). The significantly higher sea level of the Pilocene implies a loss of substantial amounts of both the Greenland Ice Sheet as well as the West Antarctic Ice Sheet. In summary, the polar ice sheets behave very differently in a 400 ppm $CO_2$ world than in a world with a maximum $CO_2$ concentration of 300 ppm, the world in which modern humans evolved.

The Palaeocene-Eocene Thermal Maximum (PETM), about 55 million years ago, provides some important clues about the response of the climate system if large amounts of fossil fuels continue to be burnt for the rest of this century. During the PETM, atmospheric $CO_2$ concentrations rose to at least 1,000 ppm; the global average air temperature was 5-6°C higher than pre-industrial levels; the hydrological cycle was intensified with increased rainfall, cyclones and megafloods; there was widespread acidification of the ocean; and there were massive impacts on terrestrial and marine ecosystems. Recovery to the pre-PETM background levels of $CO_2$ and climate took up to 100,000 years (Zachos et al., 2003; T. Naish, pers. comm.).

These dramatic past changes in climate, triggered by relatively slower and more subtle forcing compared to today's rapid increase in atmospheric $CO_2$, strengthen the imperative to reduce greenhouse gases deeply and rapidly if we wish to halt the trajectory of the climate towards these potentially catastrophic futures.

## 2.5 Synthesis: How much and how fast will the climate system respond to human pressures?

A critical uncertainty in the projections of future climate change is the degree to which the climate system responds to a given level of greenhouse gases in the atmosphere, or, more fundamentally, to a given level of radiative forcing. Observations, model projections and analyses of past climate changes all contribute insights towards addressing this question.

Two concepts are important. The first is the concept of 'equilibrium climate sensitivity'. That is, how much will the global average air temperature rise for a given increase in greenhouse gas concentrations once the climate system has reached equilibrium? Equilibrium means the point at which the climate has stabilised after the greenhouse gas concentrations level off. It estimates the level of climate change that we are ultimately committed to for a given greenhouse gas concentration target.

The second, related concept is the 'transient climate response.' This refers to the degree to which the climate system responds to an increase in greenhouse gases in the shorter term, while greenhouse gas concentrations and the climate are still changing and have not yet stabilised. The transient climate response is useful to estimate the more immediate level of changes that we will have to cope with in the next few decades.

Until recently much of the emphasis has been on estimating the equilibrium climate sensitivity. In the context of contemporary climate change, climate sensitivity is usually defined as the increase in global average air temperature that would result from a doubling of the pre-industrial $CO_2$ concentration,

after the climate system has reached a new equilibrium. A doubling of $CO_2$ would be from 280 to 560 ppm. The climate sensitivity is largely determined by the direct effect of a doubling of $CO_2$ concentration plus the fast feedbacks in the climate system (*Box 1*).

There are three basic approaches used to estimate climate sensitivity:

**Model simulations.** A common way to estimate the climate sensitivity including all fast feedbacks is to carry out multiple runs of a set of global climate models with a $CO_2$ concentration of 560 ppm. The models are run until the climate system has reached a new equilibrium. This approach yields a climate sensitivity that is likely to fall in the range 2.0-4.5°C (IPCC, 2007).

**Past climate changes.** Climate sensitivity can also be estimated by analysing past changes in the climate system, such as the transition from the most recent ice age to the present warm period, a transition that occurred from about 20,000 to 12,000 years ago. A rise in global average air temperature of about 5-6°C is associated with that transition, which also involved a rise in $CO_2$ concentration from about 180 to 280 ppm (Petit et al., 1999). The transition also involved slow feedbacks, such as changes in the large continental ice sheets in the northern hemisphere, which contributed significantly to the temperature rise but which are not normally included in analyses of contemporary climate sensitivity. When the direct warming effect of the rise in $CO_2$ concentration along with the influence of the fast feedbacks are considered, a climate sensitivity of about 3°C is often the result (e.g., Hansen et al., 2008), within the range of the estimates from the climate models.

**Contemporary observations.** Some attempts have recently been made to estimate the sensitivity of the climate system to increases in $CO_2$ concentration using the observations over the instrumental period of the last century or the last few decades (e.g., Otto et al., 2013). These approaches use indirect methods to yield an estimate of climate sensitivity since the climate during the observation period is not in equilibrium, and often yield estimates around 2°C, at the lower end of the IPCC (2007) range of 2-4.5°C. Of the three approaches, contemporary observations are arguably the most appropriate for estimating the time-dependent, evolving response of the climate to a changing $CO_2$ forcing. Unfortunately the observational record is rather short, and only captures the beginning of the climate system's response to rising $CO_2$, so this method also produces an estimate that includes a significant uncertainty range.

A synthesis of results using these three methods was published by Knutti and Hegerl (2008) and is shown in *Figure 30*. The 'likely' ranges of the various estimates mostly fall within the 2-4.5°C range of the IPCC (2007). The 'most likely' values of climate sensitivity as estimated by model simulations and by analyses of past climate changes are both close to 3°C, while 'most likely' estimates from the instrumental period and the last millennium are closer to 2°C. The Knutti and Hegerl (2008) synthesis also contrasts the strengths and weaknesses of the various approaches.

In summary, the equilibrium sensitivity of the climate to a doubling of $CO_2$ concentration is likely to fall within the 2-4.5°C range, but there is no consensus yet on a most likely value. Determining better estimates of climate sensitivity and transient climate response remains an ongoing research task, although there is broad scientific agreement that even the low-end, best-case scenario would produce significant and costly climate impacts (see *Section 4.1*; *Figure 48*).

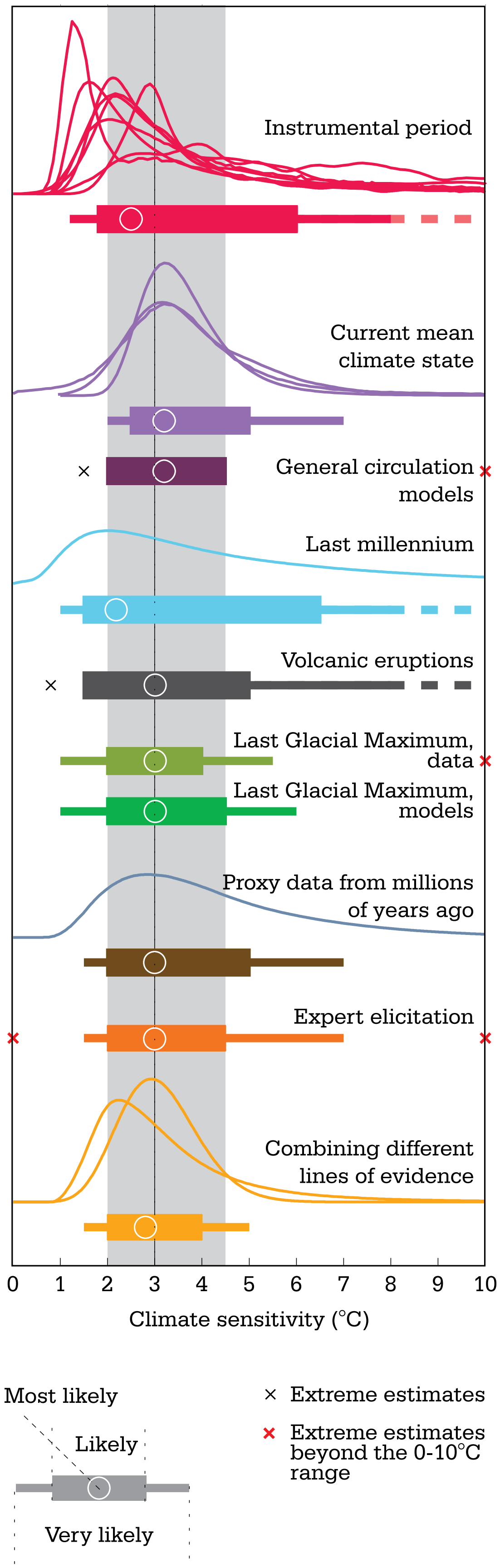



**Figure 30:** Distribution and ranges for climate sensitivity from different lines of evidence. The most likely values (circles), likely (bars, more than 66% probability) and very likely (lines, more than 90% probability) ranges are subjective estimates by the authors based on the available distributions and uncertainty estimates from individual studies, taking into account the model structure, observations and statistical methods used, Values are typically uncertain by 0.5°C. Dashed lines indicate no robust constraint on an upper bound. Distributions are truncated in the range 0-10°C; most studies use uniform priors in climate sensitivity. Single extreme estimates or outliers (some not credible) are marked with crosses. The IPCC (2007) likely range and most likely value are indicated by the vertical grey bar and black line, respectively.

**Source:** Knutti and Hegerl, 2008

# CHAPTER 3: RISKS OF A CHANGING CLIMATE

Changes in climate and weather events significantly affect our own health and well-being, our societies and economies, and the natural ecosystems that we not only enjoy in their own right but that also provide us with essential services. In fact, climate change is already affecting our lives, often in negative ways, by shifting the basic climatic conditions around which we've built industries and infrastructure and by making many extreme weather events worse by increasing their frequency or intensity.

It is important to define the relationship between the nature of the risks associated with climate change and the actual impacts that occur from a shift in climate or a weather-related event. Impacts ultimately depend on many other non-climatic factors, such as the exposure of people, infrastructure or ecosystems to the weather event or shift in climate; their sensitivity to the climatic changes; and their capacity to adapt. Together, these factors largely determine vulnerability to shifts in climate and changes in extreme weather events.

Here, we focus on how shifts in climate and changes in extreme weather events are changing risks that people and societies face. Such information is crucial to inform the debate on reducing greenhouse gas emissions. How quickly and deeply do we need to reduce emissions to stabilise the climate at an acceptable level? That is, what is the level of climate change beyond which the risks become intolerable and unmanageable and to which we simply cannot adapt? Furthermore, improved knowledge of the nature and severity of the risks associated with climate change helps us better prepare now so that we can minimise the damage that does occur when extreme events happen.

## 3.1 Changes in the climate system that have impacts

Some changes in the climate system have direct and immediate impacts, for example from increased intensity and frequency of extreme weather events. Slower changes in the climate may seem less dramatic and threatening than extreme weather events but they also can have serious consequences for our lives and livelihoods, often acting in more complex ways than the direct impacts of extreme weather.

For example, small shifts in atmospheric and oceanic circulation influence rainfall patterns, which in turn change the basic climatic conditions around which we have located our water supplies and agricultural systems. Changing these systems can be costly, such as building new dams or raising the height of existing dam walls, and can be socially

disruptive, such as relocating agricultural systems to new regions that have become climatically more suitable than the ones where the system is currently located.

In addition to these direct effects, slow changes in climate can create background stresses that increase our vulnerability to a wide range of extreme weather and non-climate related stresses. Dealing with the financial consequences of more frequent flooding, for example, can drain the financial resources of families and businesses, making them more vulnerable to economic stresses and shocks. In the natural world, the slow increase in the acidity of the ocean is reducing the calcification rates of corals, making them more vulnerable to bleaching from underwater heatwaves and to other stresses such as overfishing and sediment and nutrient loading from coastal agricultural areas.

In this chapter we first describe the slow changes in the basic state of the climate system that can reduce the resilience of human and natural systems. Some of these changes – precipitation patterns and sea-level rise – have been described earlier. Others, such as changes in atmospheric and oceanic circulation and the increase in ocean acidity, are discussed in greater detail here.

We then summarise how climate change is influencing many of the weather events that have made Australia the land of extremes – heatwaves, bushfires, heavy rains, droughts, tropical cyclones and coastal flooding. More detailed information on climate change and extreme weather events can be found in the Climate Commission's recent report *The Critical Decade: Extreme weather.*

The final section of this chapter provides an overview of the risks that climate change poses for various sectors – human health, water supplies, property and infrastructure, agriculture and natural ecosystems. This section concludes with a brief state-by-state overview of the major risks of climate change.

## Long-term changes in the climate system

### Atmospheric circulation

Atmospheric circulation is the large-scale movement of air across the surface of the Earth and throughout the atmosphere. Winds associated with the atmospheric circulation transport heat and moisture. Winds also influence the ocean circulation, which transports heat from low to high latitudes, and causes upwelling of nutrients at key locations, affecting carbon exchange between the atmosphere and the ocean. Atmospheric circulation can move vast amounts of heat and moisture from one location to another; consequently atmospheric circulation influences regional climate in profound ways.

In recent decades changes have been observed in the behaviour of atmospheric circulation. These changes include poleward displacements of major wind and pressure systems (Reichler, 2009), such as an expansion of the tropical Hadley Cells towards the poles (Reichler and Held, 2005), and a shift of the mid-latitude jet streams to higher latitudes (Frederiksen and Frederiksen, 2007). These changes in atmospheric circulation are expected to continue, and will likely have a profound influence on climate, ecosystems and societies.

Changes in atmospheric circulation are especially important because of the short time scales on which they can operate. For example, the recent decline in rainfall over southwest Western Australia has been linked to a southward migration of the Southern Hemisphere jet stream ( Frederiksen and Frederiksen, 2011; Cai and Cowan, 2006). This has led to fewer cold frontal systems reaching the Australian southwest coast (Hope et al., 2006). This has affected rainfall patterns, with profound and costly consequences for agriculture and water management over southwest Western Australia (see *Box 9*).

Changes in North Atlantic atmospheric circulation patterns may have influenced the path of Hurricane Sandy, which devastated New York City and other areas of the US Mid-Atlantic Coast in 2012. Whereas such storms tend to skirt the US coast before drifting to the northeast and dissipating at sea, Sandy took a sharp turn to the west and headed directly towards the most populous region of the US east coast. The reason for the sharp westerly turn was a high pressure cell in the North Atlantic, an atmospheric circulation pattern which is unusual for this region at the time of the year that Sandy struck the coast. These high pressure systems are possibly linked to the increasing loss of sea ice over the Arctic Ocean (Petoukhov and Semenov, 2010) (for further detail on Hurricane Sandy refer to the Climate Commission's *Was Hurricane Sandy influenced by climate change?*).

The depletion of stratospheric ozone over Antarctica in the austral spring (the 'ozone hole') may be influencing atmospheric circulation patterns in the southern hemisphere, especially during the summer season (e.g. Lee and Feldstein, 2013), and may also influence the upwelling/downwelling circulation in the Southern Ocean (e.g. Waugh et al., 2013). The Montreal Protocol has been effective in rapidly reducing the emission of the chemicals responsible for the thinning of the ozone layer in the stratosphere, thus probably averting even more drastic changes to southern hemisphere atmospheric and oceanic circulation that would occur with an ever-increasing ozone hole.

## Ocean circulation

The ocean is a major driver of global climate. Oceans redistribute large amounts of heat around the planet via the global ocean circulation – through regional scale upwelling and downwelling, via the large-scale wind-driven gyres of the subtropical oceans, and through the global overturning circulation. This redistribution of heat makes some parts of the world warmer or cooler than they would otherwise be. For example, the Gulf Stream and the North Atlantic Current – which transport heat from tropical regions northeastwards – mean that northwestern Europe experiences much warmer temperatures than those in the same latitudes in Siberia or northern Canada.

Climate change is altering the factors that control ocean circulation, such as wind, precipitation, and air temperature patterns. Changes in these factors are leading to a change in ocean circulation, which therefore could affect some regional climates.

Projections suggest that climate change will alter ocean circulation systems around Australia, potentially strengthening the East Australia Current and weakening the Indonesian Throughflow. There is observational evidence that change is already underway in some of the coupled systems that affect Australian rainfall, such as the El Niño Southern Oscillation (ENSO; Ashok et al., 2007; Taschetto and England, 2009; *Box 4*) and the Indian Ocean Dipole (IOD) (Abram et al., 2008; Cai et al., 2009a;b; Cai et al., 2011; *Box 5*).

**Box 4: What is the El Niño Southern Oscillation (ENSO)?**

The El Niño Southern Oscillation (ENSO) is a naturally occurring phenomenon that drives changes in rainfall patterns, temperatures, river flow, agricultural production and severe weather around the world – including Australia (e.g. Power et al. 1999; Callaghan and Power 2012; Richardson et al., 2011).

ENSO originates in the Pacific Ocean near the equator, where an air-sea interaction involving trade winds and surface ocean circulation drives changes in sea surface temperatures across the region (Richardson et al., 2011). During the El Niño part of the cycle (which in Australia usually means warm temperatures and reduced rainfall (e.g. Power et al. 1998) sea surface temperatures tend to increase in the central and eastern equatorial Pacific. During the La Niña part of the cycle (which in Australia usually means cooler temperatures and more rainfall (e.g. Power et al. 1998) sea surface temperatures tend to decrease in the central and eastern equatorial Pacific.

Over the past century, warming has been greater in the western than the eastern equatorial Pacific (Wu et al., 2012), and this has been linked to El Niño events becoming more severe. Recently, a changing pattern of El Niño has been noted toward 'Modoki' events where the warm water shifts from the west to the middle of the Pacific (Ashok and Yamagata, 2009; Yeh et al., 2009). 'Modoki' events are characterised by warmer-than-usual waters in the centre of the Pacific and cooler sea surface temperatures on the eastern and western parts of the ocean (Ashok et al, 2007). A 'Modoki' event occurred in 2002/2003 where, despite the actual warming being modest, the rainfall response in some regions was significant. For example, eastern Australia experienced some of its most severe reductions in rainfall during this event (Taschetto and England, 2009).

**Box 5: What is the Indian Ocean Dipole (IOD)?**

The Indian Ocean Dipole (IOD) describes the warming and cooling of waters in the tropical region of the Indian Ocean. Like ENSO, the IOD affects the climate of Australia and other countries that surround the Indian Ocean.

The IOD is divided into two phases, positive and negative. The positive IOD phase is characterised by cooler-than-normal sea surface temperatures in the tropical, eastern section of the Indian Ocean and warmer-than-normal waters in the west. A positive IOD is usually associated with a decrease in rainfall over central and southern Australia. The negative IOD period is the reverse; characterised by warmer-than-normal sea surface temperatures in the tropical eastern Indian Ocean and cooler-than-normal waters in the west. The negative IOD period usually brings increased rainfall over southern Australia.

Source: Saji et al., 1999

There has been a reported increase in the frequency of positive IOD events over the last few decades (Abram et al., 2008; Cai et al., 2009a;b). This is coinciding with recent non-uniform warming trends in the Indian Ocean (Alory et al., 2007; Ihara et al., 2008); the eastern Indian Ocean is warming at a slower rate than the western Indian Ocean (Cai et al., 2011). Such shifts in ocean circulation can profoundly influence the

surrounding regional climates and rainfall (Cai et al., 2011; IOCI, 2012).

There have also been recently observed changes to the Southern Ocean. The Southern Ocean has a major influence on global climate and the carbon cycle – it is estimated to absorb about 40% of the total ocean uptake of anthropogenic $CO_2$ (Gruber et al., 2009). The widespread influence of the Southern Ocean is a result of the unique ocean currents in this region, which efficiently transfer heat and carbon from the surface to the deep ocean, and from one ocean basin to another via the Antarctic Circumpolar Current. The Southern Ocean also interacts with Antarctica's climate and its ice, influencing the rate of ice-shelf melt, which has implications for land-ice flow into the ocean. Any long-term changes in the Southern Ocean will have significant ramifications for global and regional impacts.

There has been an observed warming and freshening through most of the Southern Ocean depth over the past 50 years (Gille, 2008; Böning et al., 2008; Meijers et al., 2011). The major currents have shifted to the south (Sokolov and Rintoul, 2009a,b), and acidity has increased as extra $CO_2$ is absorbed in the water (ACE CRC, 2008; Bindoff et al., 2007 in IPCC, 2007). Over the past 15 years, the Antarctic Circumpolar Current (ACC) has migrated slightly southward. The movement of this current has been attributed to changes in wind patterns (Cai, 2006; Downes et al., 2009) and is linked to both the ozone hole and the increase in greenhouse gases in the atmosphere (Thompson et al., 2011). Climate models suggest that the Southern Ocean will continue to evolve in response to greenhouse warming, resulting in further changes in ocean currents, ocean warming, ocean salinity, higher sea levels and less sea ice.

## Ocean acidification

The world's oceans are becoming more acidic because of their increasing uptake of $CO_2$ from the atmosphere, which generates carbonic acid (*Figure 31*). Since the Industrial Revolution, the world's oceans have absorbed 30-50% of the additional $CO_2$ released into the atmosphere (Sabine and Tanhua, 2010). The ocean's average acidity has already increased by approximately 30% since pre-industrial times – a drop of 0.1 pH unit (pH is a measure of acidity that decreases with increasing acidity) (Friedrich et al., 2012). The current rates of ocean acidification recorded at monitoring sites in the Atlantic and Pacific oceans are 100 times greater than those experienced at the end of the last ice age (Friedrich et al., 2012).

Increasing ocean acidity decreases the concentrations of carbonate ions, an essential building block for many marine organisms, such as corals, pteropods (small molluscs) and zooplankton. This impact of increasing ocean acidity is already evident (*Figure 32*). For example, some species of calcifying zooplankton in the Southern Ocean now have shells 30-35% lighter than their counterparts in pre-industrial times (Moy et al., 2009). The future of calcifying organisms has wider impacts on marine ecosystems because these organisms play important roles at the base of many marine food webs. Calcification rates have also declined in corals in the Great Barrier Reef, although thermal stress and other factors may have contributed to this trend (De'ath et al., 2009).

By the end of the century pH levels are projected to be 0.2-0.3 units below pre-industrial levels (Howard et al., 2012). When examined in the laboratory, decreases of seawater pH to levels that may be experienced later this century have a range of negative impacts on marine organisms, in addition to the direct impacts on calcifying species. High concentrations of dissolved $CO_2$, for example, impair embryonic development in Antarctic krill *Euphausia superba*

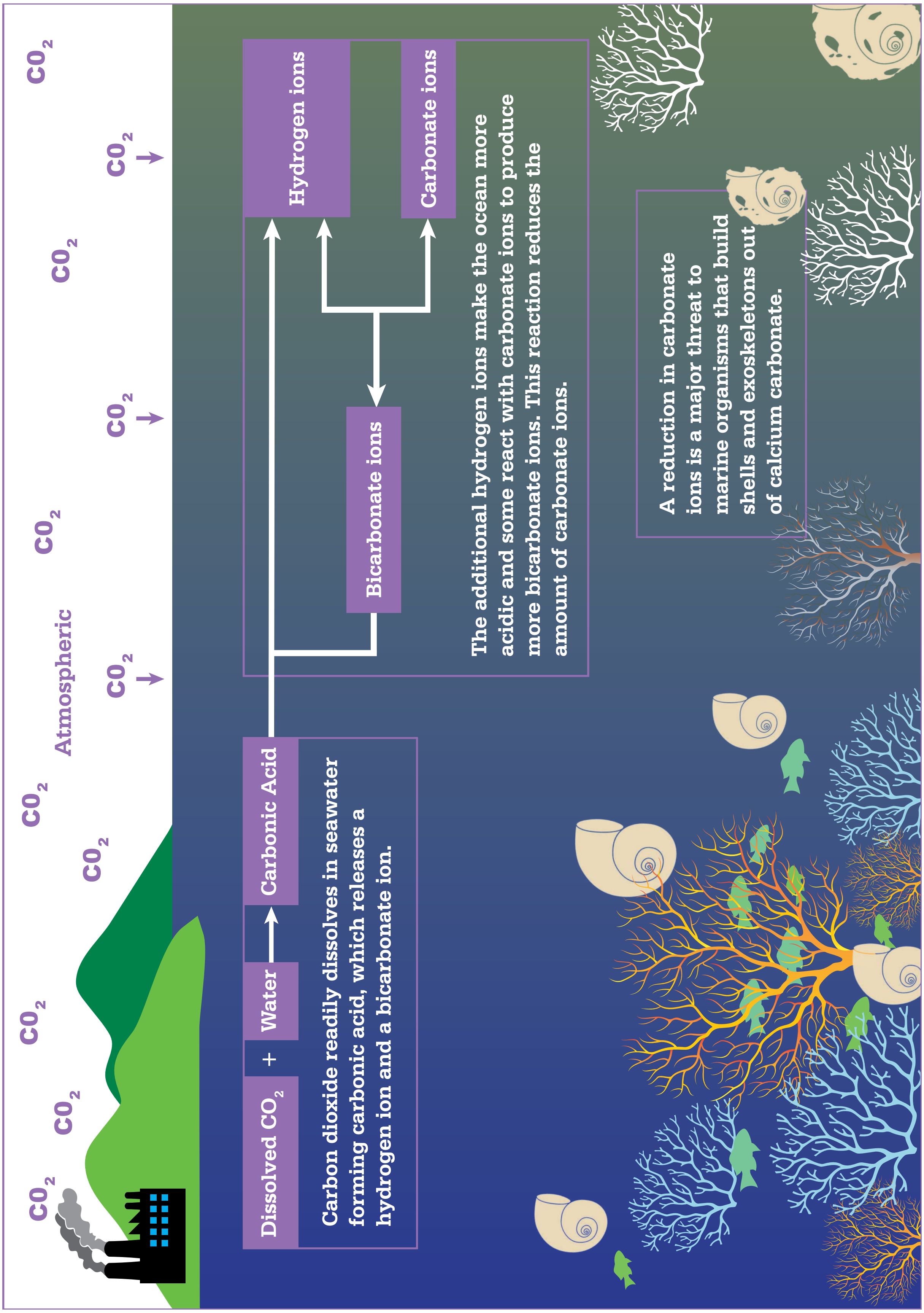



**Figure 31:** The chemistry of ocean acidification.

(Kawaguchi et al., 2011). Krill is a major food source for many animals in the Southern Ocean ecosystem. When combined with higher water temperatures, increased $CO_2$ reduces the aerobic capacity of some fish species (Munday et al., 2009a) and affects the sense of smell and habitat-finding ability of others (Munday et al., 2009b) (*Figure 33*). Declining ocean pH reduces the availability of iron, an important limiting nutrient for marine plant production (Shi et al., 2010). Ocean acidification also results in significant decreases in low-frequency sound absorption in the oceans, resulting in an increase in ambient noise levels (Hester et al., 2008). This could have impacts on military and economic interests, but also on whale communication (Hester et al., 2008; Ilyina et al., 2010).

**Figure 32:** Decreasing amounts of carbonate ions negatively affect the ability of calcifying organisms such as the pteropod *Limacina* to build and maintain its exoskeleton.

**Source:** Wikicommons/ R. Giesecke

**Figure 33:** Increasing ocean acidification affects the sense of smell in juvenile clownfish, hindering ability to navigate.

**Source:** Metatron/ Wikicommons

## $CO_2$ fertilisation

Plants obtain carbon from atmospheric $CO_2$ via photosynthesis. The increase in $CO_2$ in the atmosphere is likely to act as a 'fertiliser' and stimulate plant growth. The $CO_2$ fertilisation effect has many consequences but two potentially positive effects have often been proposed in the context of climate change: (i) the removal of $CO_2$ from the atmosphere via enhanced plant growth could act as a dampening feedback mechanism, slowing the increase of $CO_2$ in the atmosphere; and (ii) $CO_2$ fertilisation will increase crop yields. The question is how important are these effects?

The $CO_2$ fertilisation effect does not operate in isolation from other factors that affect plant growth, such as the availability of water, nitrogen, phosphorus and other nutrients. If any of these factors are in short supply, plant growth is limited, and so the $CO_2$ fertilisation effect will be diminished. Uptake of additional $CO_2$ by plants can also lead to some important side-effects, such as a reduction in the nitrogen-carbon ratio in plant leaves, making them less nutritious for herbivores (Hovenden and Williams, 2010; Robinson et al., 2012).

Several approaches have been used to study the effect of increasing atmospheric $CO_2$ on photosynthesis and ultimately on the amount of carbon stored in plants, the nutritional status of plants, and crop yields. These approaches include the application of high levels of $CO_2$ to plants in open-topped chambers or greenhouses, the fumigation of whole ecosystems or crops in the open with $CO_2$-enriched air, or observations of changes in the growth of trees and other plants and the uptake of carbon by ecosystems in the natural environment – in effect, using the fossil fuel-driven increase in atmospheric $CO_2$ as a 'natural experiment'.

Such research is now yielding a consensus about several aspects of the $CO_2$ fertilisation question. First, it is unlikely that the fertilisation effect is leading to a large additional uptake of $CO_2$ from the atmosphere; it is only a very weak dampening feedback. For example, a global-scale study estimating changes in growth using tree-ring data suggests that only about 20% of sites globally might show a $CO_2$ fertilisation effect. The authors concluded that increased $CO_2$ may change some aspects of forest dynamics, but "…$CO_2$ fertilisation of forests will not counteract emissions or slow warming in any substantial fashion" (Gedalof and Berg, 2010). An analysis of carbon gains and losses across Australia from 1990 to 2011 found that increased $CO_2$ concentrations resulted in an overall gain in carbon storage (Haverd et al., 2013). This $CO_2$ fertilisation effect was more significant in the deserts and in northern

Australia, where rainfall was above average over the two decades, than in the southwest and southeast where rainfall was below average. In the southeast and Tasmania, the carbon gains associated with rising $CO_2$ concentrations were marginally greater than the losses associated with extended drought conditions (Haverd et al., 2013).

Second, earlier conclusions from studies of crops in chambers that increased $CO_2$ will lead to substantial increases in yield, which could, in turn, offset losses from climate change, appear to be overestimates. A synthesis of experiments on major grain crops under elevated $CO_2$ in fully open-air field conditions found that yields were enhanced by only about 50% as much as in the earlier enclosure experiments, and "…cast doubt on projections that rising $CO_2$ concentrations will fully offset losses due to climate change" (Long et al., 2006). More specifically, a synthesis of 15 years of open-air $CO_2$ enrichment studies showed that the yield of wheat increased by about 15% under elevated $CO_2$, rice by about 12% and sorghum by 5% or less (Ainsworth and Long, 2004).

The bottom line is that $CO_2$ fertilisation could be important in some specific locations and circumstances, but it is not a broad-scale panacea for either the imperative to remove $CO_2$ from the atmosphere nor the need to increase food production in a changing climate. Thus, it comes nowhere near compensating for the many negative impacts on crops and food production resulting from a change of the climate due to rising concentrations of greenhouse gases, most notably $CO_2$.

## Extreme weather events

The term *extreme weather* or *climate event* refers to 'an occurrence of a value of a weather or climate variable beyond a threshold that lies near the end of the range of observations for the variable' (IPCC, 2012). It is a weather or climate event that is unusually intense or long, occasionally beyond what has been experienced before. Examples include heatwaves, very hot days, cold weather events, bushfire weather, heavy rainfall, drought, tropical cyclones, and coastal flooding (high sea-level events). By definition, extreme events occur only rarely, and they are noticeable because they are so different from the usual weather and climate and because they are associated with adverse impacts on humans, infrastructure and ecosystems.

Extreme weather events are often short-lived, abrupt events lasting only several hours up to several days; they are 'shocks' within the climate system. These are *'acute'* extreme events. A few extreme events can last for much longer periods of time, – *'chronic'* extreme events. An example is drought, which is a significant lack of rainfall over a period of months to years.

**Heatwaves and very hot days:** A heatwave is an extended period – at least three days – with persistent temperatures well above the local average (BoM, 2012). Thus, the definition of a heatwave for Hobart would be different from that for Alice Springs. An important feature of a heatwave is the amount of relief that is experienced overnight. Persistently high overnight temperatures greatly increase the impact of heatwaves, particularly on human health. 'Very hot days' and 'hot days' in Australia are defined as days with the maximum temperature greater than 40°C and 35°C, respectively (BoM, 2013e).

The duration and frequency of heatwaves across Australia have increased over the period 1971-2008, and the hottest days during a heatwave have become even hotter (Perkins and Alexander, 2013). An analysis of the long-term temperature records from 1910 to 2011 across Australia shows that record high temperatures, both maximum and minimum, occurred disproportionately in the 11 year period, 2001-2011, during which record-high temperatures have outnumbered record lows by a ratio of 2.8 to 1 (maximum) and 5.2 to 1 (minimum). Indicators of five-day extremes also show changes consistent with warming

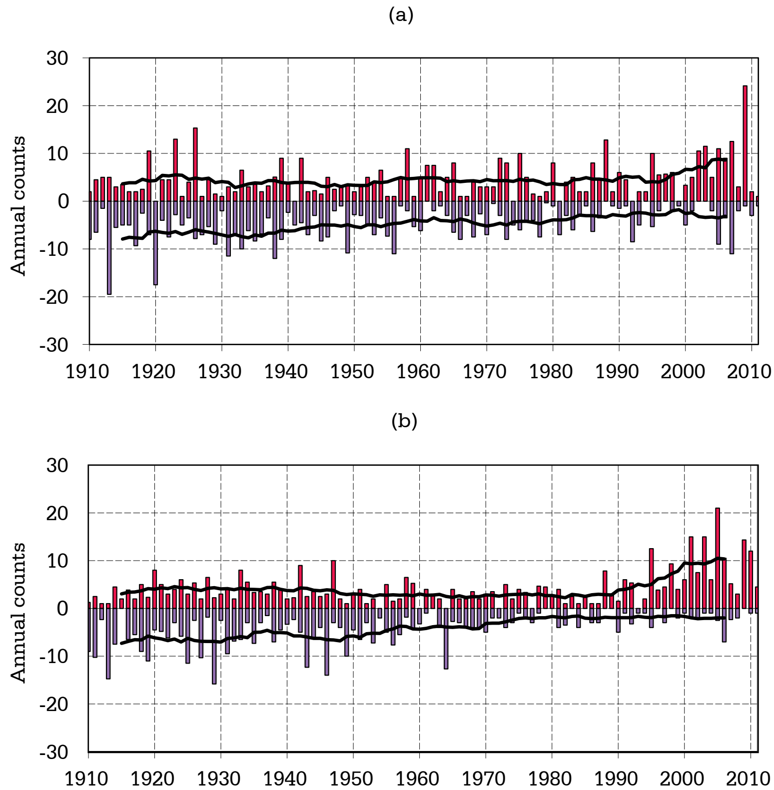



**Figure 34:** Number of record high temperatures (red bars) and record low temperatures (purple bars) per year for (a) daily maximum temperature, and (b) daily minimum temperature at Australian climate reference stations for the period 1910-2011.

Source: Trewin and Smalley, 2013

but those changes are mostly less pronounced than those for single-day extremes (Trewin and Smalley, 2013; *Figure 34*). The summer of 2012/2013 was remarkable in the number of high temperature records that were set and the intensity and extent of extreme heat (see the Climate Commission's *The Angry Summer* report). Globally, it is very likely that there has also been an increase in the number of warm days and nights (IPCC, 2012), and an increase in the intensity, frequency and duration of heatwaves (Perkins et al., 2012).

It is likely that human influences have already led to the increase of daily maximum and minimum temperatures globally (IPCC, 2012). This influence of climate change is easy to understand. As additional greenhouse gases continue to build up in the atmosphere, they trap more heat at the Earth's surface (see *Section 1.2*). This extra heat not only raises the average temperature of the air at the Earth's surface, it increases the probability that very hot weather will occur. It basically loads the dice towards more extreme heatwaves and hot days (Hansen et al., 2012). *Box 6* shows the statistical relationship between a shift in average temperature and the incidence and severity of extreme hot and cold weather.

**Box 6: The relationship between average temperature and extreme hot weather**

A small increase in average temperature can have a surprisingly large effect on the number of hot days and record hot days. *Figure 35* shows this relationship. When the average temperature is shifted to a slightly higher level, the effect on the extreme ends of the temperature range (the 'tails') is pronounced. The likelihood of extreme cold weather goes down while the likelihood of extreme hot weather goes up. In addition, new record hot weather (the heavy shaded area at the extreme right) occurs after the shift in the climate to a warmer state. This means that we are beginning to see extreme hot weather and heatwaves that have not been observed since instrumental records began, such as the record hot weather in the summer of 2012/2013 (see *The Angry Summer* report). In addition, events that were extremely rare in the previous climate are becoming more common. As expected from *Figure 35*, over a long period of time the number of record hot days per year across Australia is going up, while the number of record cold days per year is decreasing (*Figure 34*).

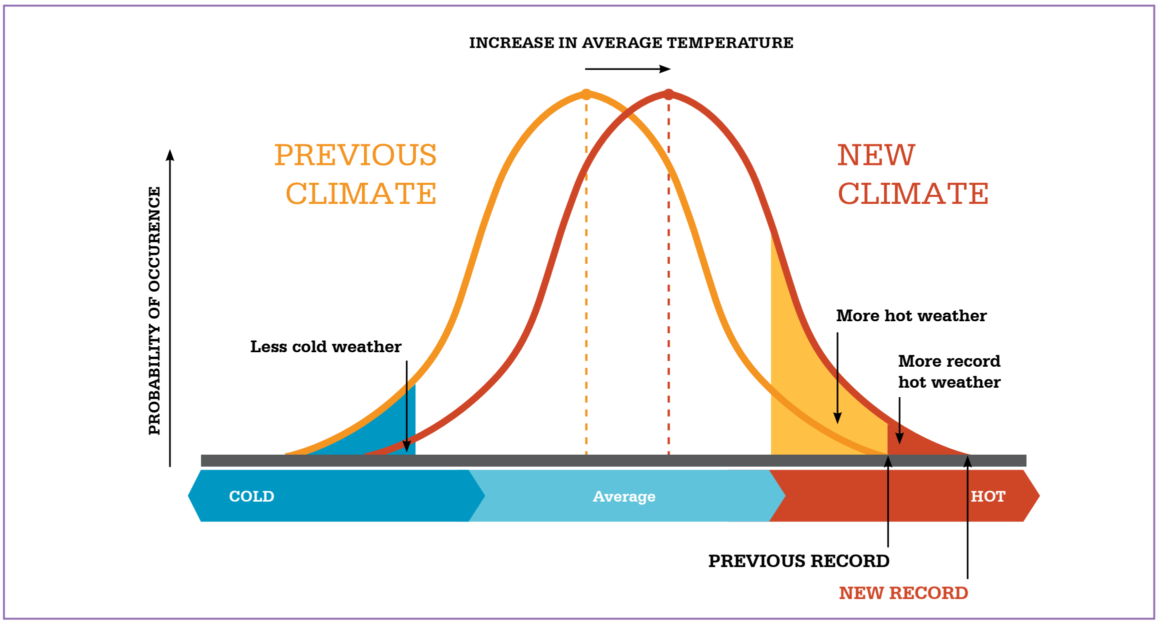



**Figure 35:** Relationship between average and extremes, showing the connection between a shifting average and the proportion of extreme events.

**Source:** Modified from IPCC, 2007.

As even more heat continues to accumulate in the atmosphere, the number of heatwaves across Australia is projected to increase significantly by the end of the century (Alexander and Arblaster, 2009), and hot days in Australia's capital cities will become much more common (*Table 1*). Globally, it is virtually certain that the frequency and magnitude of warm daily temperature extremes will increase through the 21$^{st}$ century (IPCC, 2012).

| | LONG-TERM AVERAGE (1961-1990) | 2000-2009 AVERAGE | 2030 PROJECTED | 2070 PROJECTED (low emissions scenario) | 2070 PROJECTED (high emissions scenario) |
|---|---|---|---|---|---|
| MELBOURNE | 9.9 | 12.6 | **12** (11-13) | **14** (12-17) | **20** (15-26) |
| SYDNEY | 3.4 | 3.3 | **4.4** (4.1-5.1) | **5.3** (4.5-6.6) | **8** (6-12) |
| ADELAIDE | 17.5 | 25.1 | **23** (21-26) | **26** (24-31) | **36** (29-47) |
| CANBERRA | 5.2 | 9.4 | **8** (7-10) | **10** (8-14) | **18** (12-26) |
| DARWIN | 8.5 | 15.7 | **44** (28-69) | **89** (49-153) | **227** (141-308) |
| HOBART | 1.2 | 1.4 | **1.7** (1.6-1.8) | **1.8** (1.7-2.0) | **2.4** (2.0-3.4) |

**Table 1:** The long-term average number of hot days per year (above 35°C) compared to the 2000-2009 average and the projected number for 2030 and 2070 for some Australian capital cities. Both the 2030 and 2070 projections show the median and, in brackets, the range of projections for the number of hot days. The lowest number in the range is the 10th percentile and the highest number is the 90th percentile of the various model projections. The median is the 50th percentile. The 2070 projections are divided into low and high emissions scenarios. Brisbane and Perth are not included because the locations of observations for these cities differ from the locations on which projections are based.

Source: BoM, 2013f; CSIRO and BoM, 2007

**Bushfire weather:** Bushfire weather refers to the daily weather conditions that are conducive for the outbreak of a fire – very hot, dry and windy days. Longer-term weather and climate conditions can also affect bushfires through effects on the amount and condition of the fuel load, which is also influenced by a range of non-climate-related ecological factors.

Daily weather variables related to wind, humidity and heat are combined with longer-term climatic variables used as indicators for the condition of vegetation to generate fire danger indices for forests and grasslands. Based on this approach, many regions in Australia have already experienced an increase in extreme fire weather as shown by changes in the Forest Fire Danger Index (FFDI) (Clarke et al., 2012). Between 1973 and 2010 the FFDI increased significantly at 16 of 38 weather stations across Australia, with no stations recording a significant decrease (Clarke et al., 2012). The main factors contributing to increased extreme fire weather are prolonged periods of reduced rainfall and increased intensity and frequency of extreme heat (Lucas et al., 2007). The increase in extreme fire weather has been most prominent in southeast Australia, where there has also been an extension of the fire season into November and March.

Climate change is increasing the probability of extreme fire weather by increasing the frequency and intensity of very hot days and hot periods. The projected increase in severity and frequency of climatic conditions that influence bushfire weather, such as higher temperatures and increased aridity, will very likely lead to an increase in frequency of extreme fire danger days in the southeast and southwest of the continent. The FFDI is projected to increase significantly in regions with uniform rainfall through the year and in winter rainfall regions, which mainly occupy southeast Australia (Clarke et al., 2011).

An increase in bushfire weather is not just an issue for Australia. Other regions around the world are also expected to see increased bushfire (or wildfire) weather including North America. Wildfire activity in the western United States increased substantially in the late 20th century and the increase is caused by higher temperatures and earlier snowmelt (Westering et al., 2006 in IPCC,

2012). Similarly, increases in wildfire activity in Alaska from 1950 to 2003 have been linked to increased temperatures (Karl et al., 2009 in IPCC, 2012).

**Heavy rainfall:** A heavy rainfall event is a deluge of rain that is much longer and/or more intense than the average conditions at a particular location. An extreme rainfall event may also be defined by its 'return period'. For example, a 1-in-20 year event is the daily rainfall total that would be expected, on average, to occur only once in 20 years.

The number of heavy rainfall events in many regions of the world is increasing (IPCC, 2012). Across Australia, there is considerable variability in rainfall and rainfall extremes. Northwest Australia has experienced a significant increase in the frequency of heavy rainfall events (IPCC, 2012; Donat et al., 2013a). In comparison, in the southeast and southwest of Australia there has been a slight decrease (not statistically significant) in the number of heavy rainfall events (Donat et al., 2013a).

According to the basic physics of the climate system, increasing temperatures of the surface ocean waters lead to more evaporation, and a warmer atmosphere can hold more water vapour. These effects result in more rainfall, with an increasing share of the rain coming as heavy rainfall events (*Figure 36*). In short, the water cycle intensifies as the climate warms. Observations are consistent with this understanding of the basic physics. There has been an increase in evaporation from the surface ocean as shown by increasing

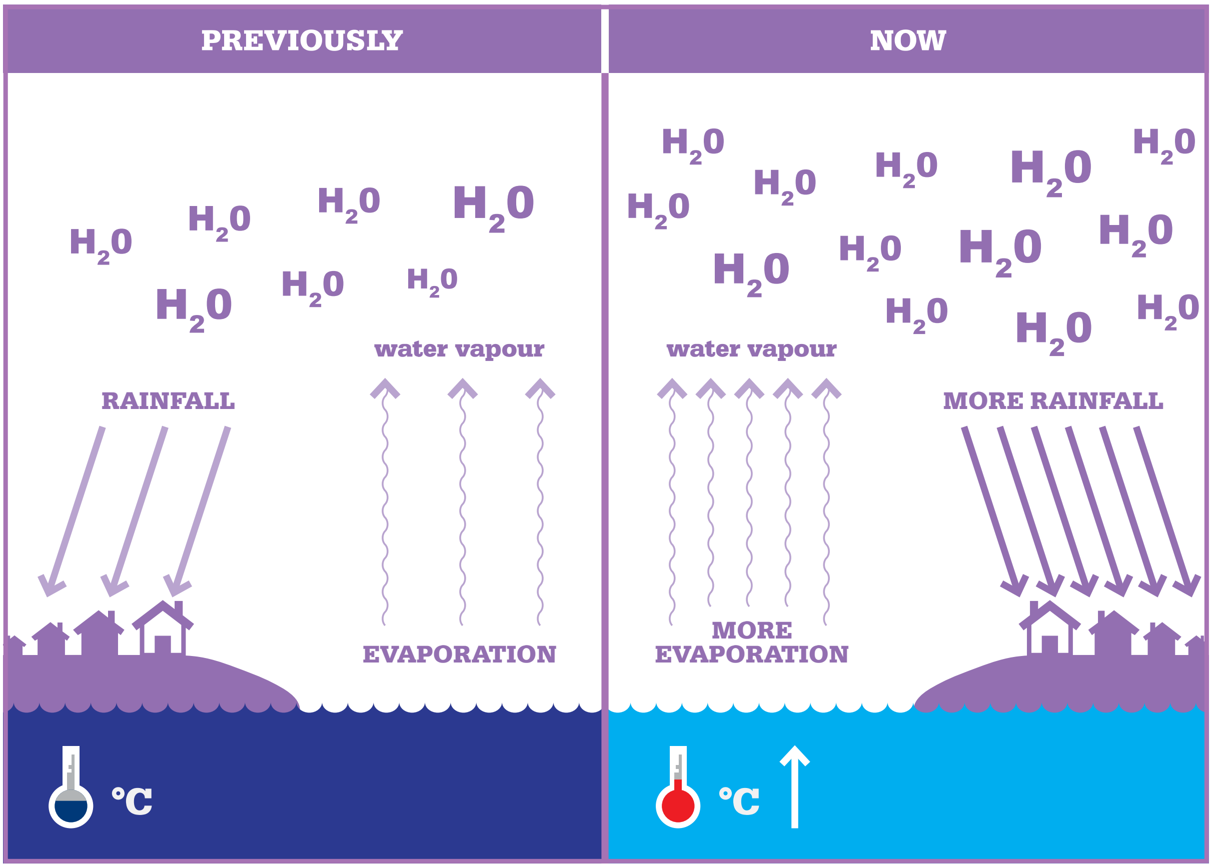



**Figure 36:** The influence of climate change on the water cycle. LEFT: The pre-climate change water cycle. RIGHT: The water cycle operating under higher surface ocean and air temperatures. The symbol $H_2O$ represents water vapour.

salinity in many areas, (Durack and Wijffels, 2010) and an increase of water vapour in the atmosphere has been measured from 1988 to 2004, the period over which reliable measurements are available (IPCC, 2007). With more water vapour in the air, average precipitation has increased in many parts of the world, with a higher share of the precipitation coming as heavy falls (IPCC, 2012; Donat et al., 2013b).

As surface ocean and air temperatures continue to rise, it is likely that the frequency of heavy precipitation, or the proportion of total rainfall from heavy falls, will continue to increase in the 21st century over many areas of the globe (IPCC, 2012). Regions where there is high confidence that the intensity and frequency of heavy precipitation are likely to increase include northern Europe, Alaska, northwest and east Canada, Greenland, Iceland, east Africa and northern Asia and central Europe in winter (IPCC, 2012). For Australia, it is more likely than not that heavy rainfall events will become more frequent, and the larger, rarer events (currently 1-in-20 year events) may increase in intensity (Rafter and Abbs, 2009).

**Drought:** Drought is a period of abnormally long, dry weather compared to the normal pattern of rainfall (BoM, 2013g). More specifically, we focus here on 'meteorological drought,' when there is a period of insufficient rainfall compared to the long-term average (IPCC, 2012), although other sectors also use concepts such as agricultural drought and hydrological drought.

Global trends in drought are inconclusive, with various studies finding inconsistent results, depending largely on the choice of index used to characterise drought (IPCC, 2012). There are, however, some trends at the regional level. For example, since the 1950s southern Europe and West Africa have experienced more intense and longer droughts (IPCC, 2012). As noted in *Section 2.1*, the southwest corner of Western Australia and much of eastern Australia have become drier since the 1970s (*Figure 16*), especially in the cooler months of the year. The Millennium Drought of 1997-2009 was one of Australia's most severe droughts, with significant impacts on urban water supplies, agricultural production and natural ecosystems. In contrast, most of the western part of the continent, particularly the northwest, has become wetter (IPCC, 2012).

Climate change is likely to be influencing drought in the southwest and the southeast of Australia in two ways – reduced rainfall and increased temperatures. This has occurred over southern Australia as climate affects the airflows that bring rainfall to this region in the autumn and winter months. Long-term changes to the atmospheric circulation across southern Australia have resulted in higher pressure, fewer cold fronts and less rainfall from rain-bearing weather systems across southwest Australia since the 1970s and across the southeast from the mid-1990s (Hope et al., 2006; Frederiksen et al., 2010; Hope et al., 2010; Timbal et al., 2010; Timbal and Drosdowsky, 2012).

This trend is projected to continue over the coming decades (Thompson et al., 2011). In addition to reduced rainfall, rising temperatures are making the impacts of droughts more severe by increasing the stress on plants and animals (McVicar et al., 2012).

Globally, projections indicate increased frequency of hot years and increased variability in rainfall (IPCC, 2007). There is medium confidence that droughts will intensify in the 21st century in some seasons and areas due to reduced precipitation and/or increased evapotranspiration (IPCC, 2012). As a general rule, regions that are currently dry are expected to become even drier and wet regions to become wetter (Trenberth, 2012).

In Australia, areas that are already experiencing increased drought conditions are likely to see more droughts in the future (Hennessy et al., 2008b; IPCC, 2012). Reductions in rainfall coupled with an

expected increased frequency of very hot days and hot periods (Kirono and Kent, 2010; Kirono et al., 2011) will likely exacerbate the severity of drought conditions in the drier parts of Australia.

**Tropical cyclones:** Tropical cyclones are intense low-pressure atmospheric systems that form over warm, tropical waters and have gale force winds.

Unequivocally determining changes in cyclone behaviour is difficult because of limited data sets and questions about data reliability going back in time, with consistent data on cyclone intensity only available since the start of the modern satellite era in the early 1980s. However, an understanding of the physical relationship between warmer surface oceans and the atmosphere suggests that cyclone behaviour is already being influenced by climate change.

Climate change can affect cyclone behaviour in two ways. First, the formation of cyclones is affected by the vertical gradient in temperature through the atmosphere – that is, the difference in temperature near the Earth and the temperature higher up in the atmosphere – and by increasing surface ocean temperatures. Cyclones form more

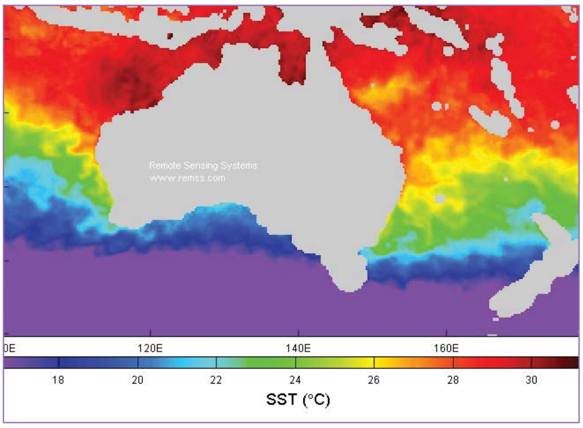



**Figure 37:** The sea surface temperatures (SSTs) around Australia immediately following the passage of cyclone Yasi across the Queensland coast. The yellow area of cooler water off the North Queensland coast shows how the cyclone drew energy (heat) from the water as it formed and tracked to the coast.

**Source:** Remote Sensing Systems

readily when there are very warm conditions at the ocean surface and the vertical gradient is strong. Second, increasing sea surface temperature increases the intensity of cyclones, both in terms of maximum wind speeds and the intensity of rainfall. Tropical cyclones draw energy from the surface waters of the oceans, and as more energy is stored in these upper waters, the cyclones have a larger source of energy to draw upon (*Figure 37*; Emanuel, 2000; Wing et al., 2007).

Projections into the future suggest that tropical cyclones are likely to become more intense but are not likely to increase in overall number (IPCC, 2012). That is, in the future we are likely to see more high-intensity cyclones and fewer low-intensity cyclones.

**Coastal flooding (high sea-level event):** Coastal flooding, often called a 'high sea-level event', is caused by wind-driven waves combined with a storm surge, with the worst impacts experienced during high tides. Storm surges normally accompany tropical cyclones and intense low-pressure systems.

By increasing the base level of the ocean, sea-level rise exacerbates the effects of a storm surge (*Figure 38*). Global sea level has risen by about 0.2 m from 1880 to 2000, which has already led to an increase in the incidence of high sea-level events. For example, in Fremantle there has been a 3-fold increase in high sea-level events since 1950 compared to the earlier decades. The Torres Strait Islands are particularly vulnerable to a rising sea level. Major coastal inundation events in 2005, 2006, 2009 and 2010 affected houses, roads, cultural sites and community gardens (Green, 2006; Green et al., 2008).

As discussed in *Section 2.2*, global sea level is rising for two main reasons – the expansion of the volume of ocean water as it warms and the addition of new water from melting glaciers and icecaps and from both melting and ice discharge from the polar ice sheets. Loss of ice from the large polar ice sheets will play an increasingly large role in the continuing rise of sea level through

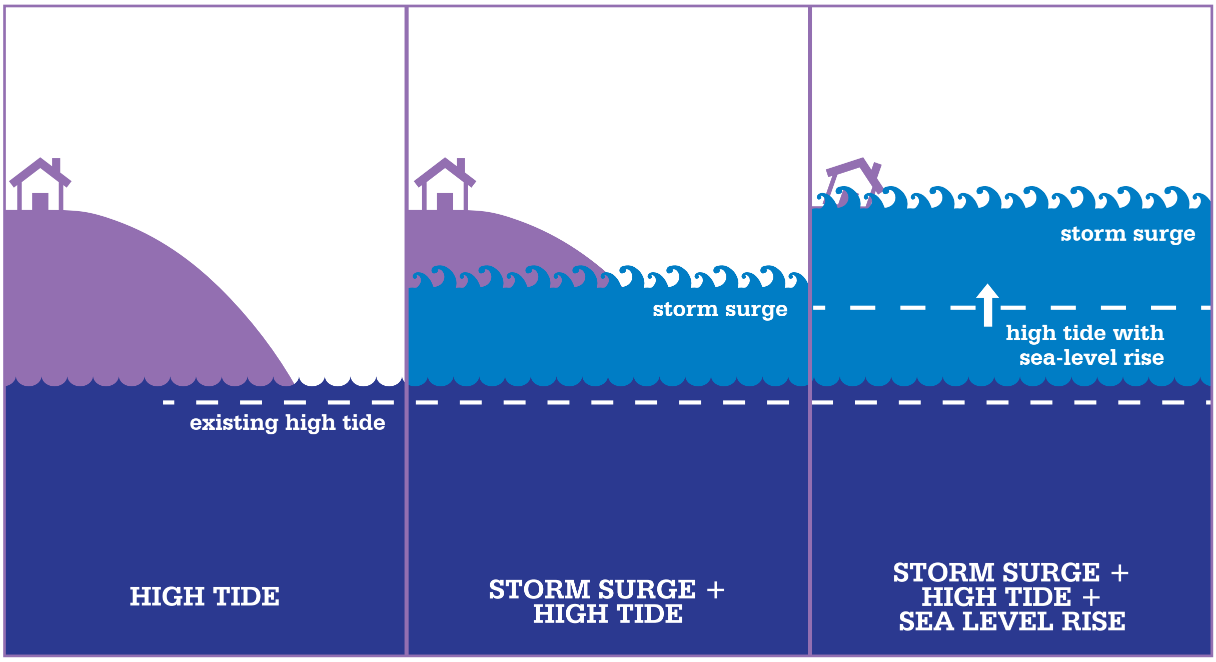



**Figure 38:** Rising sea level is increasing the base level for a storm surge.

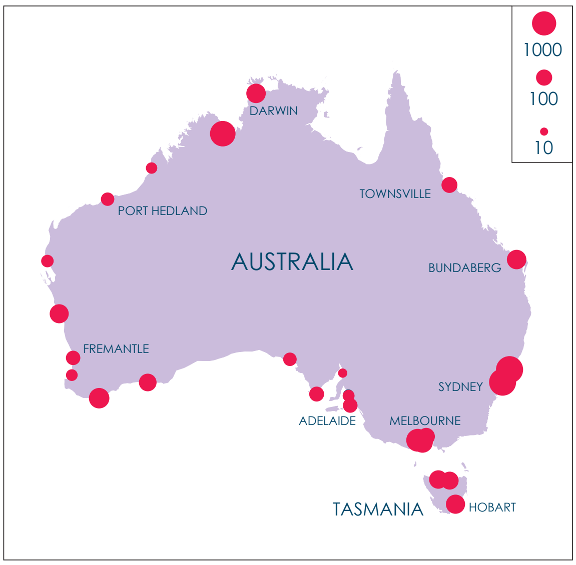



**Figure 39:** Projected increase in frequency of flooding events from the sea for a sea-level rise of 0.5 m.

**Source:** Hunter, 2012

this century and beyond. The projections for sea-level rise by 2100, compared to the 1990 baseline, range approximately from 0.2 m to 0.8 m but higher levels cannot be ruled out (IPCC, 2007; see *Section 2.2: Sea-level rise*).

Projections have also been made for the increase in frequency of high sea-level events for sites along the Australian coastline (*Figure 39*). A sea-level rise of 0.5 m can lead to large increases in the frequency of coastal flooding, typically by a factor of several hundred and in some places by as much as one thousand (Hunter, 2012). An increase in frequency of 100 means that an extreme event that currently occurs, on average, only once in 100 years, would occur every year.

**Box 7: Examples of direct and indirect impacts of climate change on health**

Direct risks include:

- More frequent and intense heatwaves resulting in more heart attacks, strokes, accidents, heat exhaustion and death;
- More frequent or intense extreme weather events – particularly storms, floods and cyclones – resulting in more injuries, deaths and post-traumatic stress; and
- Larger and more intense fires, increasing the number of cases of smoke-induced asthma attacks, burns and death.

Risks of indirect, flow-on effects, although more complex and harder to predict in timing and extent, include:

- More exposure to some air pollutants and air-borne allergens, such as pollens and moulds, exacerbating respiratory illnesses such as asthma and hay fever, and longer-term heart and lung diseases;
- Changed rainfall patterns – increases in rainfall in some regions and decreases in others – and hotter temperatures increasing the spread and activity of disease-transmitting mosquitoes; increasing the chances of food-borne infection; and leading to reduced supply and increased price of some foods, resulting in reduced nutrition;
- Warming and drying in some regions leading to economic stress and, in turn, a higher prevalence of mental health problems and lower morale in rural communities; and
- Increased pressure on health systems and emergency responses delaying effective delivery of health care.

## 3.2 The risks of climate change by sector

### Health

Climate change is a major threat to our health and wellbeing (Costello et al., 2009) both directly, such as through increased temperatures, and indirectly, such as through greater exposure to air pollutants and air-borne allergens (*Box 7*).

Often considered the silent killer, heatwaves cause more loss of life than any other natural hazard in Australia, with over 4,000 fatalities attributable to heatwaves during the period 1803-1992 (Coates, 1996), twice the number of deaths due to either floods or cyclones (Coates, 1996; Loughnan et al., 2013). People most vulnerable to heatwaves include the elderly, children, and those already suffering chronic disease (Klinenberg, 2002; Loughnan et al., 2013).

Humans can only survive when their core body temperature remains within a narrow range, around 37°C (Hanna et al., 2011). If the body produces or absorbs more heat (for example, from physical activity or high air temperatures) than it can remove through direct transfer to the surrounding air or through sweating, core body temperature will rise. If core body temperature exceeds 38°C for several hours, the body can suffer heat exhaustion and reduced mental and physical capacity (Parsons, 2003; Berry et al., 2010). Serious heatstroke and even death can occur after a relatively short time if core body temperature goes above 42°C (Parsons, 2003). Projections based on a 3-4°C temperature rise show significant increases of heat stress in many parts of the world, and if the very upper ranges of the IPCC projections for 2100 are realised, some currently populated parts of the world may become uninhabitable for humans (Sherwood and Huber, 2010).

Recent heatwaves around Australia have increased hospital admissions and fatalities. The Queensland heatwave of January 2000

caused 22 excess deaths and 350 injuries (Auditor General of Queensland, 2004); the Brisbane 2004 heatwave caused an estimated 75 excess deaths (Tong et al., 2010); and the Victorian heatwave of January 2009 led to an estimated 374 excess deaths (DHS, 2009).

In recent years major heatwaves have also caused devastation in Europe and Russia. The five hottest summers in Europe since 1500 all occurred after 2002, with the heatwave events of 2003 and 2010 being exceptional years (Barriopedro et al., 2011). The 2003 heatwave caused an estimated 70,000 heat-related deaths in Europe (IPCC, 2012) while the 2010 Russian heatwave caused an estimated 55,000 heat-related deaths (Barriopedro et al. 2011). Higher mortality during very hot days has also been observed in tropical cities including Bangkok, Thailand; Delhi, India; and Salvador, Brazil (IPCC, 2012). As climate change continues, people across the world will experience even more days of extreme heat and related health impacts.

The increased frequency and intensity of extreme weather events other than heatwaves also pose risks to human health including injuries, disease and death, and disruption to health services. For example, the 2010/11 Queensland floods killed 35 people and affected about 2.5 million people (QFCI, 2011). The floods also caused costly damage to existing health infrastructure (Queensland Health, 2011), as well as indirectly affecting health through damage to sewerage and wastewater systems.

Climate change is also likely to pose a risk to our health indirectly. Changes in temperature, rainfall and humidity in Australia may allow mosquito-borne infectious diseases, such as dengue fever and Ross River virus, to become more widespread. The main carrier of dengue fever, the mosquito *Aedes aegypti*, is typically confined to northern Queensland where outbreaks occur almost annually (Ritchie et al., 2009; Russell et al., 2009). The geographic region suitable for the transmission of dengue is expected to expand southwards along the Queensland coast and into northern New South Wales over this century (Bambrick et al., 2008; *Figure 40*).

In addition, increasing climate variability and temperature may boost the prevalence of bacteria, parasites and viruses; which in turn could increase the risk of food and water contamination. For example, hotter temperatures can lead to higher incidence of

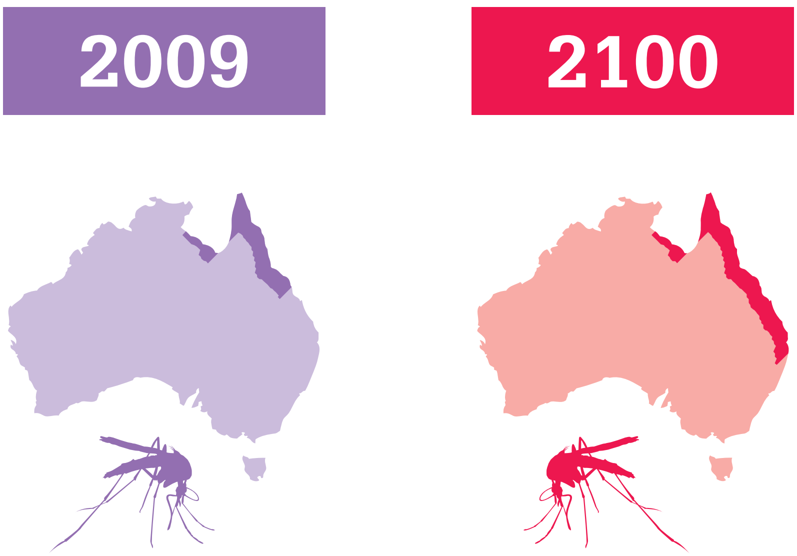



**Figure 40:** Potential spread of dengue fever by 2100, shown by shaded area. This diagram is indicative only and is drawn from in-text references. The actual future distribution of the mosquito carrying dengue fever will be determined not only by the climate but also by other changes in technology and population.

food-borne disease because many infectious agents such as *Salmonella* bacteria are sensitive to temperature and multiply more readily as the temperature rises. This increases the risk of gastroenteritis.

Extreme weather events can also make it more difficult to maintain food hygiene, water quality and sanitation practices. For example, flooding can cause sewage and farm run-off to enter drinking water supplies, leading to outbreaks of waterborne diseases such as cryptosporidiosis and giardiasis, a common cause of gastroenteritis (Karanis et al., 2007). Heavy precipitation events are strongly correlated with the outbreak of waterborne illnesses; 51% of waterborne disease outbreaks between 1948 and 1994 in the United States were preceded by precipitation events in the top decile (Curriero et al., 2001 in IPCC, 2012).

The health impacts of climate change will vary from region to region and among people of different ages and states of health and wealth. People most at risk are largely those already most vulnerable in society – the very young, the aged, people with existing medical problems, those who work outdoors, those in remote Indigenous communities and tourists (Bennett et al., 2011).

For further information on climate change and health see the Climate Commission's *The Critical Decade: Climate change and health.*

### Water supplies

Australia is the world's driest inhabited continent. The impacts of climate change on Australia's water resources are therefore of critical importance for our communities, agriculture, industries and environment. River flows in Australia vary substantially from year to year and decade to decade, exacerbating the multiple conflicting demands on our water supplies.

Predicting future changes in rainfall, and therefore water availability, is subject to far more uncertainty than projections of future temperature (see *Section 2.2*). Climate models generally predict ongoing drying in the southeast and southwest, with obvious risks to water availability for urban areas and agriculture. However, they predict a range of possible outcomes for northern Australia. To further complicate matters, water availability is not just affected by rainfall. Rising temperatures will increase evaporation and reduce runoff, and any future changes in vegetation cover could also have feedbacks to local rainfall patterns (McVicar et al., 2010).

Climate change will also affect groundwater. Recharge of groundwater systems may decline in the southern, southwestern and central parts of the continent, but increase in the north and some parts of the east (Crosbie et al., 2012).

Changes in water supplies also pose significant risks in many other countries. Twenty-five % of the current African population has limited water availability and is thus drought-sensitive (IPCC, 2012). Even those who do experience relative water abundance do not always have access to safe drinking water and sanitation (IPCC, 2012). Changing rainfall patterns, for example observed increase in drought conditions in West Africa, pose significant risk to water supplies which are already drought sensitive. The retreat of glaciers in the Himalaya and changes in rainfall are also expected to pose significant risk for south Asian water supplies.

### Property and infrastructure

The effects of climate change – including rising temperatures, changes to rainfall patterns, sea-level rise and more intense extreme weather events – have serious consequences for our property and infrastructure.

Climate change is likely to affect much of Australia's infrastructure, including commercial and residential buildings, utilities (such as energy and water services) and transportation systems, in a variety of ways.

- The energy sector is likely to be affected by extremes including stronger winds (damage to power lines), extreme heat (increased cooling demand and reduced electricity transmission) and drought (lack of water for cooling in power stations).
- More frequent drought and extreme rainfall events are expected to affect the capacity and maintenance of storm water drainage and sewerage infrastructure, drinking water quality and water demand for agricultural and domestic needs.
- Transportation systems in flood-prone areas are expected to be affected by heavy rainfall events and consequent flooding (NCCARF, 2012).
- Many types of coastal infrastructure and property will be affected by inundation during high sea-level events (*Box 8*).

Much of our existing infrastructure has not been designed to withstand the expected effects of extreme weather events exacerbated by climate change. The full range of risks to property and infrastructure is mostly foreseeable from our existing knowledge about how we have been affected by recent extreme weather events.

The prolonged extreme heat in Melbourne in January 2009 caused substantial damage to critical infrastructure, including energy transmission and rail transportation. Unprecedented demand and faults to the transmission system made the entire grid vulnerable to collapse (QUT, 2010). Melbourne's train and tram networks suffered widespread failures caused by faults to air conditioning systems and tracks buckling in the extreme heat (QUT, 2010; *Figure 41*).

The 2010/2011 Queensland floods caused significant damage. About 78% of Queensland was declared a disaster zone (QFCI, 2011). Major damage occurred to infrastructure, including thousands of kilometres of road (*Figure 42*) and rail, as well as to electricity generation and distribution to other essential infrastructure. Over 3,000 km of Queensland Rail track were affected, much of the electrical

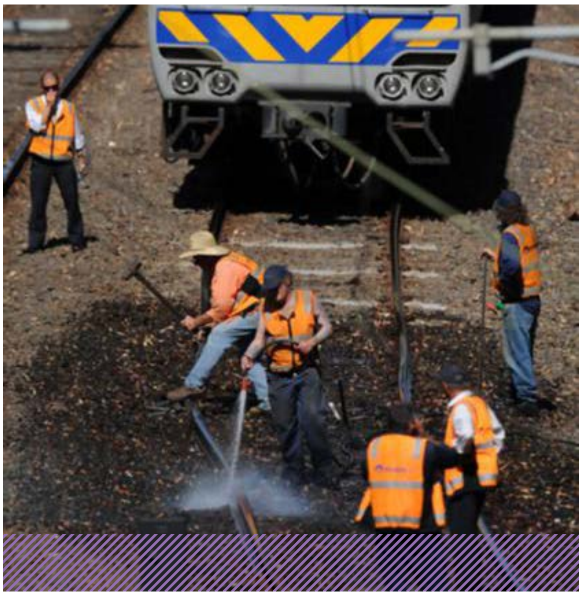


**Figure 41:** Maintenance officers in Melbourne work on train tracks that buckled under the extreme heat of 28 January 2009.

**Source:** Herald Sun

infrastructure in the Lockyer Valley was destroyed (QFCI, 2012), and approximately 29,000 homes and businesses were inundated (QFCI, 2011).

The dramatic increases in the frequency of coastal flooding with even a relatively small sea-level rise (see *Section 3.1: Coastal flooding*) mean that Australia's coastal infrastructure faces much higher risks of inundation and damage over the coming decades (*Box 8*).


**Figure 42:** Flooded road on 10 January 2011 in Stanthorpe, Queensland

**Source:** Flickr/mgjefferies

**Box 8: The risk that sea-level rise poses to Australia's coastal infrastructure**

Nationally, the combined value of commercial, light industrial, transport and residential buildings at risk from a sea-level rise of 1.1 m is approximately $226 billion (2008 replacement value) (DCCEE, 2011).

Much of Australia's commercial buildings, industrial facilities, airports, ports, hospitals, schools, roads and railways and many residential buildings are in close proximity to the coast, putting much property and infrastructure at risk from sea-level rise (DCC, 2009). The Australian Government has modelled the impact of a 1.1 m sea-level rise above 1990 levels (upper end scenario for 2100) on Australian coastlines (DCC 2009; DCCEE 2011). It found that the coastal assets at risk from the combined impact of coastal flooding and erosion include:

- 5,800 to 8,600 commercial buildings, with a value ranging from $58 to $81 billion (2008 replacement value);
- 3,700 to 6,200 light industrial buildings, with a value of between $4.2 and $6.7 billion (2008 replacement value); and
- 27,000 to 35,000 km of roads and rail, with a value of between $51 and $67 billion (2008 replacement value) (DCCEE, 2011).

For a sea-level rise of 1.1 m, Queensland has the greatest combined risk of all states and territories, in terms of both the total number of properties and infrastructure and their replacement value (DCCEE, 2011). However, coastal communities outside of capital cities generally have less capacity to adapt than their city counterparts and therefore may be more adversely affected by climate change impacts (DCC, 2009). Remote Indigenous communities in northern Australia and those living on low-lying Torres Strait islands are particularly vulnerable to sea-level rise (DCC, 2009; Green et al., 2009).

**Figure 43:** Coastal erosion at Main Beach, Gold Coast, Queensland, in March 2013.

**Source:** Flickr/Citt

Sea-level rise also poses significant risks to some of the world's largest cities and ports. By 2070 the top 10 cities in terms of assets exposed to a one-in-100 year storm surge-induced flood event are expected to be Miami, USA; Guangzhou, China; New York, USA; Calcutta, India; Shanghai, China; Mumbai, India; Tianjin, China; Tokyo, Japan; Hong Kong, China; and Bangkok, Thailand (Nicholls et al., 2007). This study defined assets as buildings, transport infrastructure, utility infrastructure and other long-lived assets. Miami currently has US$416.29 billion worth of assets exposed to a one-in-100 year flood event; this is expected to grow to more than US$3,300 billion by 2070 (Nicholls et al., 2007). This study also found that 90% of the total estimated asset exposure in 2070 is from only eight nations; China, the United States, India, Japan, the Netherlands, Thailand, Vietnam and Bangladesh (Nicholls et al., 2007).

## Agriculture

Australia produces 93% of its domestic food requirements and exports 76% of its agricultural production (DAFF, 2010). Agriculture is a significant contributor to the Australian economy; the gross value of agricultural production in 2009-10 was $39.6 billion (ABS, 2013b). In the same financial year, cattle contributed the most to agricultural value, followed by wheat, milk, vegetables, fruit and nuts and sheep (ABS, 2013b).

Agriculture is highly sensitive to variations in climate. Climate variability is not new for Australian agriculture and many producers have managed to adapt to a highly variable and challenging climate, coping with droughts, heatwaves, frosts, bushfires and flooding. However, the changing climate is presenting new challenges, including reduced productivity and profitability in some locations and industries, while presenting new opportunities in others.

There may be some limited benefits for agricultural industries from rising atmospheric $CO_2$ because some plants can become more efficient at using water in a high $CO_2$ environment (see also *Section 3.1: $CO_2$ fertilisation*). However, most benefits are likely to be outweighed by the negative impacts of a changing climate. For example, higher $CO_2$ concentrations mean that plant matter is less nutritious, due to a reduction in protein levels (Taub et al., 2008). Even a doubling of $CO_2$ concentration in the atmosphere, which would cause dramatic changes to the global climate, is unlikely to offset rainfall declines of greater than 10% (Crimp et al., 2002).

Water demand and availability will be the most critical determinant of future agricultural productivity, especially in irrigation areas. Irrigation accounts for about 50% of total water consumption, 70% of which is in the Murray-Darling Basin (Quiggin et al., 2008), and generates 30% of the gross value of Australian agriculture. But higher temperatures and changes in the frequency and/or intensity of extremes events such as droughts, floods and bushfires will also be important. Some of the impacts of a changing climate on selected agricultural products are discussed below.

**Beef and dairy:** Increasing temperatures are likely to have adverse effects for cattle by increasing the frequency of heat stress, especially for those cattle in feedlots, and reduce overall productivity in the beef, sheep and wool sector (McKeon et al., 2009). Animals with heat stress have reduced appetite, produce less milk and milk of a lower quality, grow more slowly and are less likely to breed (QFF, 2008; DEEDI, 2010). In extreme circumstances, heat stress can lead to mortality.

Increasing temperatures could also drive a southerly shift in the distribution of pests and parasites, such as cattle ticks and buffalo fly, which cause injury to cattle (IPCC, 2007), increasing the risk of infection and disease, and reducing production (QFF, 2008).

**Broadacre cropping:** As the climate changes, wheat yields may be sustained or even increased by altering sowing dates and using different cultivars in many regions (Crimp et al., 2008; Luo et al., 2009). The challenges to sustain yields will be particularly large in areas that undergo the most serious reductions in rainfall, such as southwest Western Australia (*Box 9*).

**Box 9: The wheat-belt of Western Australia**

Southwest Western Australia, an important grain-producing area, has been undergoing a drying trend since the 1970s. The decline in rainfall in the Western Australian wheat-belt is greater than reductions in any other wheat-growing region in Australia (Asseng and Pannell, 2012). Changing rainfall and higher temperatures could result in a reduction of up to 30% of 1999 yields by 2050 (van Gool, 2009).

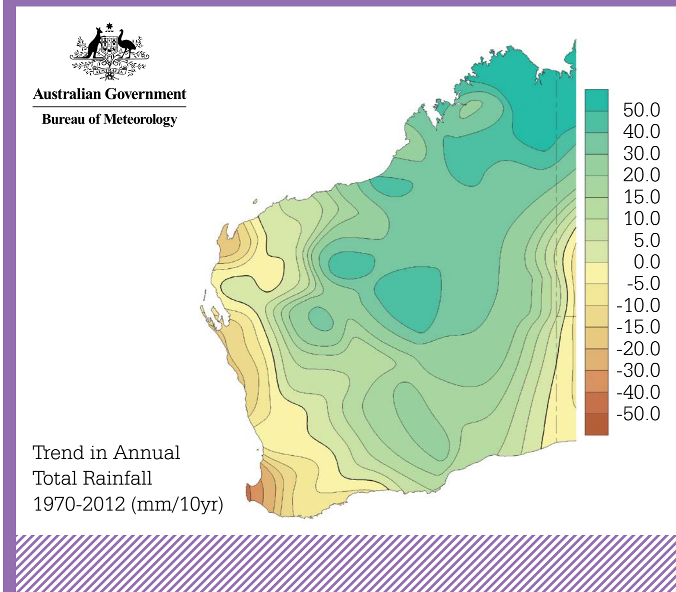



**Figure 44:** Figure showing the long term trend in total annual rainfall from 1970-present in Western Australia

**Source:** BoM 2013h

In some cases, despite the significant drop in rainfall in the Western Australian wheat-belt, farmers have adapted (Farre et al., 2009) through improvements in technology and management practices, such as the adoption of no-till cultivation to conserve soil moisture (Agtrans Research, 2009) and the use of previously waterlogged land (Ludwig et al., 2009). Wheat growers in southwest Western Australia could adapt to climate change if they have access to improved crop varieties and technologies, and where sound business management approaches are adopted (Kingwell et al., 2013).

**Fruit and vegetables:** Horticultural industries are more sensitive than many other agricultural sectors to climate change, particularly changes in temperature and reduced rainfall (Deuter et al., 2006). As the climate shifts, some crops will not be able to be grown where they are grown now. Heat stress, increased irrigation demand, reduced chilling and maturing times, and increased pest and disease problems are likely (QFF, 2008).

Extreme weather events can also have a significant impact on the availability and cost of fruit and vegetables. For example, cyclones Yasi and Larry destroyed many banana crops, leading to a shortage of bananas and significant price increases.

**Wine:** As the life-cycle of wine grapes is predominantly temperature-driven (Jones and Davis, 2000; Pearce and Coombe, 2004), a changing climate could influence wine grape production and quality across Australian wine regions (Webb et al., 2007; *Figure 45*). Substantial decreases in the climate suitability of current wine-producing regions may be felt by 2050, especially in those regions that have a Mediterranean climate (Hannah et al., 2013).

Grapes have been ripening earlier, with increased temperatures and declines in soil water content driving this change (Webb et al., 2012). In southern Australia grape harvesting was advanced eight days per decade over

**Figure 45:** Vineyard in McLaren Vale, South Australia

**Source:** Flickr/Keturah Stickann

1985-2009 (Webb et al., 2012). Similar effects have been observed in regions in France and Germany, where grape harvesting has also advanced eight (1972-2004) and four days per decade (1955-2004), respectively (Webb et al., 2012).

This shift in the time of ripening will vary from region to region and variety to variety (Smart et al., 1980). For example, cooler climates such as those in Tasmania and the Mornington Peninsula in Victoria should allow the successful ripening of varieties that were previously unsuitable (Smart, 1989). However, with increasing temperatures, ripening in regions that are currently suitable for wine grape cultivation may be accelerated to the point that, for some grape varieties, the suitability of the region will be reduced (Webb et al., 2007).

**Cotton:** Any significant reduction in average rainfall in the Murray-Darling Basin in the winter growing period could reduce availability of water for irrigation in spring and summer, resulting in lower cotton production (QFF, 2008). It is estimated that without effective global action to reduce emissions, irrigated agriculture in the Murray-Darling Basin could decline by up to about 70% by 2050 (Garnaut, 2008).

**Forestry:** Forestry contributes about 0.6% of annual GDP (ABARES, 2012b). Changes in water availability will have the most important impact on future productivity, with plantations in southwest Australia at most risk (Medlyn et al., 2011a). Modest reductions in rainfall may be partially offset by the fertilisation effects of increasing $CO_2$ (Simioni et al., 2009) but the long term impacts of rising $CO_2$, together with the potential future effects of weeds, pests, fire and disease, are poorly understood, making predictions highly uncertain (Medlyn et al., 2011b).

The impacts of climate change on food production is also a global issue (*Box 10*), with a changing climate likely to make the task of feeding a growing population even more challenging.

**Box 10: Climate change risks for global food production**

Production of crops and livestock requires, among other things, suitable temperatures and sufficient water supply. Climate change is placing added pressure on the capacity of the world's food producers to feed the growing population. Drought, floods and high temperatures, all of which are influenced by climate change, can cause reductions in food production (IPCC, 2012). For example, in developed countries, climate change could reduce wheat yields by about 4% by 2050, and 14% by 2080 (Nelson et al., 2010). In Africa and South Asia, climate change could reduce crop yields by about 8% by the 2050s (Knox et al., 2012).

In recent years, extreme weather events such as heatwaves, droughts, floods and wildfires in major food producing countries have contributed to rising food prices (Garnaut, 2011). In fact, extreme heat may be one of the most serious threats to maintaining food production in a warming climate (Battisti and Naylor, 2009). Growing populations and reduced yields due to climate change are expected to lead to higher food prices in future; wheat prices could be about 23% higher in 2050 due to climate change (Nelson et al., 2010).

The effects of climate change on food production are particularly significant for regions of the world that already have pressures on food security. In many developing countries, it is common for households to consume most of the food they produce, while also depending heavily on food production for income (IPCC, 2012; Knox et al., 2012). With lower yields, these households may be at risk of shortages of food for their own consumption and for generating income.

Climate change also presents challenges for countries where food security may not be of major concern, as illustrated by the effects of recent droughts. New Zealand experienced one of the worst droughts on record in early 2013, with a cost estimated at NZ$1 - 2 billion (Ministry for Primary Industries, 2013). Climate change is expected to cause more droughts in New Zealand, with a 10% increase in time spent in drought considered likely for the eastern agricultural regions by the middle of this century (NIWA, 2011).

### Natural ecosystems

Australia is home to 7-10% of the world's species (Mittermeier et al., 2007) and is considered one of the most biologically diverse countries in the world. Our rich biodiversity has been shaped by the continent's long history of isolation from other land-masses, highly variable climate, infertile soils, flat topography, and long history of human impacts. These factors will also determine the vulnerability of our fauna and flora to future change, and their capacity to adapt. Our ecosystems are already subject to considerable stresses, including habitat loss and degradation, pests and weeds, over-allocation of river flows, over-harvesting of commercial species, and pollution. Climate change will interact with, and in many cases exacerbate, these existing threats (Steffen et al., 2009).

Some projected changes may occur incrementally, as average climatic conditions gradually shift – changes in the boundaries between different vegetation types, such as we have already observed between rainforests and savannas (see *Section 2.1*), are an example. Significant ecological impacts are associated with some of these shifts. For example, the long-spined sea urchin *Centrostephanus rodgersii* has extended its range from NSW into Tasmanian

coastal waters, in line with warming sea temperatures and the strengthening of the East Australian Current (Banks et al. 2010; *Figure 46*). This urchin feeds on kelp, and its growing population in Tasmania has had devastating impacts, with the local disappearance of over 150 species that use the kelp as habitat (Ling, 2008).

Other changes could occur far more abruptly, driven by changes in the frequency and intensity of extreme weather events such as bushfires, droughts, cyclones and heatwaves.

Mortality of many plants and animals during recent droughts has been well documented, including frogs in southeast Australia (MacNally et al., 2009), cider gums in the sub-alpine areas of Tasmania (Calder and Kirkpatrick, 2008), and trees in northeast savanna woodlands (Fensham et al., 2009). Tree growth rates were reduced 45-80% and tree mortality increased 5-60% across a 50,000 ha eucalyptus forest during the drought periods 2002-2003 and 2006-2007 at Tumbarumba, near Canberra in southeast Australia (Keith et al., 2012). These drought stress factors, coupled with insect damage that was linked to the drought conditions, demonstrated a reduced capacity of the forest to store carbon (Keith et al., 2012).

Heatwaves on land and in the sea have also had severe impacts. On a single day in 2002, for instance, air temperatures exceeded 42°C in areas of southeast Australia, killing over 3,500 flying foxes (Welbergen et al., 2008). Since 1994 over 30,000 flying foxes have died during 19 similar events. In Western Australia, heat stress is likely to have caused the deaths of over 200 Carnaby's Black cockatoos in January 2010 (Saunders et al., 2011).

Marine heatwaves have had impacts on many species, especially on coral reefs. Extreme sea surface temperatures can lead to a physiological stress response in which the corals expel their symbiotic zooxanthellae, a phenomenon called coral bleaching (*Figure 47*). There are no records of bleaching occurring along the Great Barrier Reef prior to 1979; since this time at least seven have occurred. The most serious of these, in 1998 and 2002, affected up to 60% of individual reefs (Hughes, 2012). The first-ever reported bleaching at Ningaloo Reef in Western Australia occurred in 2011 (Wernberg et al., 2013). To date, there is limited evidence that corals will be able to adapt to ongoing thermal stress (Hoegh-Guldberg, 2012), although this is a very active and somewhat controversial area of research.

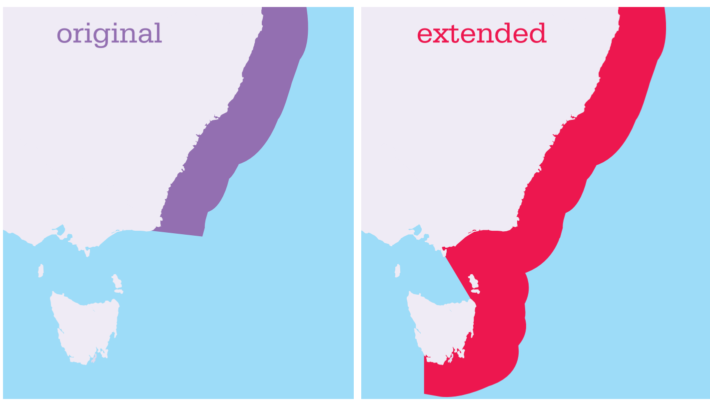



**Figure 46:** The range of the long-spined sea urchin is extending southward, consistent with warming sea temperatures and the strengthening of the East Australian Current. The left image depicts the historical distribution of the sea urchin along the mainland Australian coast. The right image demonstrates the recently extended range into Tasmanian waters.

**Source:** Redrawn from Banks et al., 2010

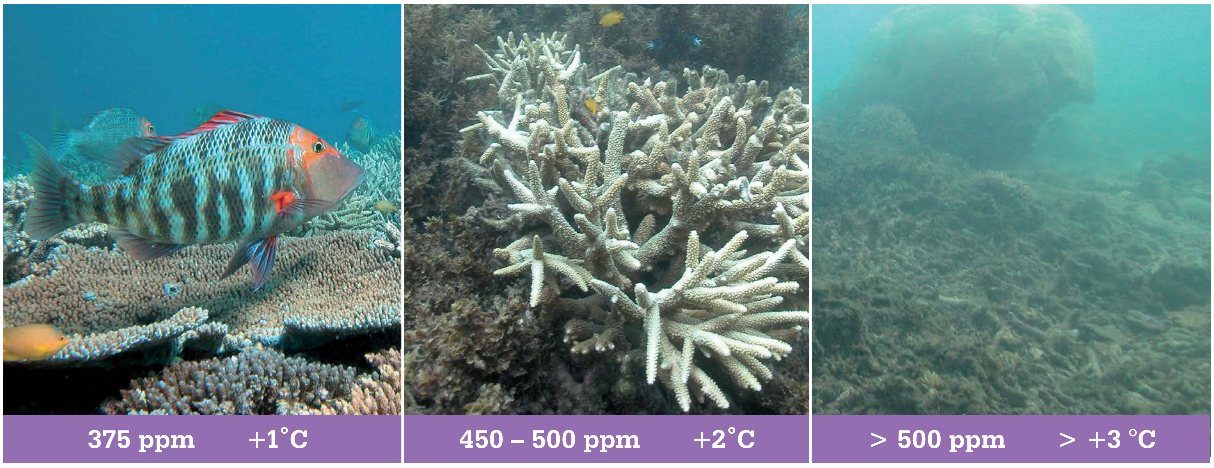



**Figure 47:** Anticipated reef states under varying carbon dioxide concentrations.

**Source:** modified from Hoegh-Guldberg et al., 2007

Species Distribution Models, which use the relationships between the present day geographic distribution of a species and the climate within that distribution, can be used to predict the location of suitable habitats under future climates. These techniques have been applied to a wide range of species, including koalas (Adams-Hosking et al., 2011), kangaroos (Ritchie and Bolitho, 2008), banksias (Fitzpatrick et al., 2008), butterflies (Beaumont and Hughes, 2002), fish (Bond et al., 2011), and platypus (Klamt et al., 2011). The results consistently predict that many species will suffer considerable reductions in available climatic habitat in the future, even after making fairly optimistic assumptions about the ability of species to migrate to new areas. Some species may suffer complete loss of suitable climate areas, greatly increasing the risk that they will go extinct (Hughes, 2012). The climate space of 101 Australian terrestrial and inland water birds is likely to be entirely gone by 2085 (Garnett et al., 2013). Exposure is likely to be greatest for birds confined to the Cape York Peninsula, the Wet Tropics, the Top End of the Northern Territory, the central and southern arid zone, southern South Australia and King Island (Garnett et al., 2013).

As the distributions, life cycles, and population sizes of individual species are affected by the rapidly changing climate, flow-on impacts to ecological communities and ecosystems will become increasingly evident. An analysis of potential changes in vegetation communities predicts dramatic and continent-wide changes in their structure and composition by mid-century, with a general decline in environments favouring trees and an increase in open woodlands, chenopod shrublands and grasslands (Dunlop et al., 2012).

Some ecosystems are considered at greater risk, in the short to medium term, than others. The alpine zone, which has already suffered significant loss of snow cover over the past few decades, and is home to many rare and threatened species, is considered one of the most vulnerable regions. Rising sea levels pose substantial risks to low-lying coastal wetlands, such as those in Kakadu National Park (BMT WBM, 2011). Other regions of concern include inland freshwater and groundwater systems subject to drought, over-allocation and altered timing of floods; tropical savannas subject to changed fire regimes; and biodiversity-rich regions such as southwest Western Australia and rainforests in Queensland (Hughes, 2011; Laurance et al., 2011).

## 3.3 The risks of climate change for Australian states and territories

The following snapshots exemplify the risks that climate change poses for Australian states and territories.

# AUSTRALIAN CAPITAL TERRITORY

**Population:** 376,500
**Capital:** Canberra
**Area:** 2,358 km$^2$

A changing climate is affecting the lifecycle of the endangered Northern Corroboree Frog and its habitat. Increasing temperatures are likely to alter the timing of breeding, affecting egg and tadpole development. Additionally, the species is only found in small sub-alpine region bog environments of the Bimberi and Brindabella ranges, and in the Bogong Mountains and Fiery Ranges in New South Wales. Increasing temperatures and reduced rainfall are likely to reduce this limited habitat even further (NSWSC, 2010; ACTESDD, 2013).

Increasing temperatures are also likely to increase the number of heat-related deaths in the Australian Capital Territory (Bambrick et al., 2008).

The Australian Capital Territory is expected to experience an overall reduction in annual rainfall, with greater reductions in winter and spring rainfall (CSIRO, 2012).

Changing rainfall patterns are likely to threaten the Australian Capital Territory's water supply through reduced rainfall and runoff into the Cotter and Googong catchments.

The number of days above 35°C per year is expected to increase from 5.2, the long-term average, to 8 by 2030. By 2070, Canberra could have between 10 and 18 days with temperatures above 35°C (CSIRO and BoM, 2007). During the 2000-2009 decade Canberra experienced an average of 9.4 days per year over 35°C.

Canberra may have an annual average of 19 to 25 very high or extreme fire danger days by 2020 and 22 to 38 days by 2050, compared with the present average of 17 days (Lucas et al., 2007).

Canberra has experienced a reduction of 5 frost nights per decade between 1970 and 2012 (BoM in CC, 2013) and is likely to experience less frosts in the future (CSIRO and BoM, 2007). Canberra currently experiences on average 63.8 days of frost each year. The number of frost days could decline by between 5 and 27% by 2050 (CSIRO and BoM, 2007).

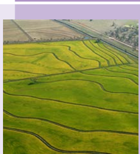
**Image sources (clockwise from top).** Northern Corroboree Frog: Environment and Sustainable Development Directorate, ACT; Canberra frost: Ben Laurence-Rogers/Flickr; Bushfire: Poster2602/Flickr; Cotter Dam in 2008: CSIRO Publishing.

# NEW SOUTH WALES

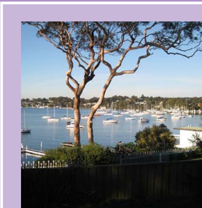
**Population:** 7,314,100
**Capital:** Sydney
**Area:** 800,642 km²

A changing climate is likely to be beneficial for the cane toad. The cane toad's distribution is likely to extend further into the state, mostly along the northern coastal region (Caley et al., 2011) – posing a significant risk to biodiversity.

The expected increase in hot days and in consecutive dry days and droughts across the southeast of Australia will very likely lead to increased frequencies of days with extreme fire danger (DECCW, 2010). The Forest Fire Danger Index (a measurement of bushfire risk) is expected to increase strongly in regions with uniform rainfall through the year and in winter rainfall regions, which mainly occupy southeast Australia (Clarke et al., 2011).



Climate change is likely to affect agricultural production in the Murray-Darling Basin through changes in water availability, water quality and increased temperatures. For example, reduced rainfall may affect productivity from irrigated agriculture (Quiggin et al., 2010).



Between 40,800 and 62,400 residential buildings may be at risk of inundation from a sea-level rise of 1.1 m and storm tides associated with a one-in-100 year storm – the highest number of residential buildings at risk of any state in Australia (DCC, 2009). Local government areas most at risk include Lake Macquarie, Wyong, Gosford, Wollongong, Shoalhaven and Rockdale (DCC, 2009).

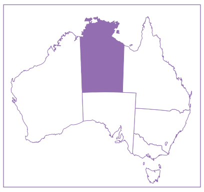
Southwest regions of New South Wales are expected to experience a decrease in winter rainfall – which is when most of the runoff in this region occurs – translating to a considerable reduction in winter and annual runoff (CSIRO, 2012).

Average temperature in Sydney is expected to increase by between 0.6°C and 1.3°C by 2030 compared to 1990 levels (CSIRO and BoM, 2007; CSIRO, 2011). State-wide the greatest increases in average maximum temperature are expected to occur in the north and west of the state (CSIRO and BoM, 2007; DECCW, 2010).

A changing climate will make some areas less climatically suitable for some species of plants and animals and more climatically suitable for others. For example, the endangered mountain pygmy-possum is restricted to elevations above the winter snowline. Reductions in snow, coupled with high summer temperatures, may subject the species to considerable stress (Steffen et al., 2009; DECCW, 2010).

**Image sources (clockwise from top).** Cane toad: !p4ul/Flickr; Toronto at Lake Macquarie: Hullwarren/Wikicommons; Pygmy possum: Therese Cobcroft; Irrigated agriculture in the Murray-Darling Basin: Arthur Mostead.

# NORTHERN TERRITORY



**Population:** 236,300
**Capital:** Darwin
**Area:** 1,349,129 km²

Average temperature in Darwin is expected to increase by between 0.7°C and 1.4°C by 2030 compared to 1990 levels (CSIRO and BoM, 2007; CSIRO, 2011). Central regions of the Northern Territory are expected to experience greater warming than its coastal areas (CSIRO and BoM, 2007).

Kakadu National Park is one of Australia's natural ecosystems most vulnerable to the impacts of climate change (BMT WBM, 2011). Sea-level rise will lead to saltwater intrusion, posing a significant threat to freshwater wetland systems (BMT WBM, 2011). Up to 80% of freshwater wetlands in Kakadu could be lost, with rises in average temperatures of 2-3°C (ANU, 2009). Increased intensity of cyclone activity, altered fire regimes, accelerated erosion from sea-level rise and storm-surges, and changes in vegetation are also expected to affect Kakadu (ANU, 2009).

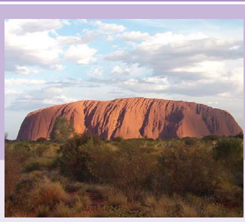
The largest increase in sea level around Australia has been observed in the northern and western regions of the continent. Darwin has observed a rise in sea level of 8.3 mm per year (from 1990 to 2011). Groote Eylandt on the Gulf of Carpentaria has observed a rise in sea level of 8.9 mm per year (from 1993 to 2011) (NTC, 2011).

Increasing temperatures are likely to affect beef production in northern Australia, due to heat stress in cattle. The distribution of cattle tick and buffalo fly is likely to shift south, increasing the risk of infection, disease and reduced production in newly exposed regions (ABARES, 2012c).

Tourism is the largest employing industry in the Territory (Tourism NT, 2013) and contributed $648 million to the Australian economy in 2010-11 (DRET, 2012). A decline in environmental values in the Territory could result in reduced numbers of visitors.

Climate change is likely to exacerbate existing health risks and create new risks for Indigenous people and remote communities. These risks include increased exposure to heat stress, fire, diseases, extreme rainfall events and flooding (Green et al., 2009).

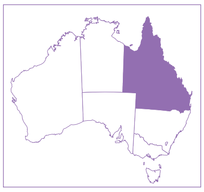
A changing climate also poses risks to significant cultural values including cultural sites and rock art (ANU, 2009; BMT WBM, 2011).



In Uluṟu-Kata Tjuṯa National Park, rising temperatures are likely to lead to increased drought, reduced runoff due to higher evaporation and changing fire regimes (ANU, 2009).

**Image sources (clockwise from top).** Kakadu: Tourism NT/Wikicommons; Beef cattle: Arthur Mostead; Uluru: Sputnikcccp/Wikicommons; Tourism: Skittledog/Flickr.

# QUEENSLAND



**Population:** 4,584,600
**Capital:** Brisbane
**Area:** 1,730,648 km²

Tropical cyclones are likely to become more intense but are not likely to increase in number (IPCC, 2012).

Many Torres Strait Islands are already vulnerable to flooding, but rising sea levels will worsen this risk. Sea level in the Torres Strait region has been rising at double the global average, at approximately 6 mm per year (Suppiah et al., 2011).

Climate change poses multiple, serious threats to the Great Barrier Reef (Johnson and Marshall, 2007; Hoegh-Guldberg, 2012). Sea surface temperature 1-2°C above the average summer maximum (based on the period 1985-93, excluding 1991-92) can cause mass coral bleaching (Hoegh-Guldberg et al., 2007) and lower growth rates (De'Ath et al., 2009). If high temperatures (2-3°C above normal) are prolonged or persistent (more than eight weeks) bleached corals will die in increasing numbers. Corals and other marine organisms are also likely to be affected by ocean acidification, rising sea levels, increasing coral diseases and physical damage from any intensification in tropical cyclones (Veron et al., 2009).

Plants and animals in the high altitude areas of the Wet Tropics are especially vulnerable to climate change with this particular environment likely to disappear by 2070 (Williams et al., 2012). Many species in this region are already at the limits of their range and face high rates of extinction from rising temperature and potential reductions in rainfall (Shoo et al., 2011). Animals such as the mahogany glider and lemur-like ringtail possum and many bird species could lose a large portion of climatically-suitable habitat (Steffen et al., 2009; Garnett et al., 2013).

Tourism contributes about $17.5 billion to the state's economy and directly employs about 124,000 (TQ, 2013). A decline in environmental values including the Wet Tropics and Great Barrier Reef and cultural values such as the Gold Coast could result in decreased tourist numbers.

The number of heat-related deaths is expected to increase significantly throughout the 21st century, depending on the level of warming (Bambrick et al., 2008).

By 2030, average temperature is expected to have risen by 1°C compared to 1990 levels (CSIRO and BoM, 2007). Temperature rises are very likely to be greater in inland areas than coastal regions (CSIRO and BoM, 2007).

Between 35,900 and 56,900 residential buildings may be at risk of inundation from a sea-level rise of 1.1 m – the second highest number of residential buildings at risk of any state in Australia (DCC, 2009). Local government areas most at risk are Moreton Bay, Mackay, the Gold Coast, Fraser Coast, Bundaberg and the Sunshine Coast (DCC, 2009).

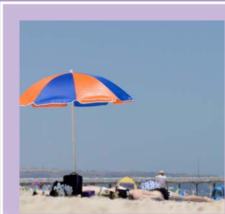
**Image sources (clockwise from top).** Inundation at Saibai Island, Torres Strait: Torres Strait Regional Authority; Great Barrier Reef: Great Barrier Reef Marine Park Authority; Gold Coast: Tourism Australia; Wet Tropics: Tourism Australia.

# SOUTH AUSTRALIA

**Population:** 1,658,100
**Capital:** Adelaide
**Area:** 983,482 km²

Remote indigenous communities such as those in the Alinytjara Wilurara region will be vulnerable to climate change impacts, particularly from hazards such as fire and floods (Bardsley and Wiseman, 2012).

Rainfall is expected to decline overall across South Australia, with declines most notable in winter and spring (Pinkard and Bruce, 2011).



Average temperature in Adelaide is expected to increase by between 0.6°C and 1.3°C by 2030 compared to 1990 levels (CSIRO and BoM, 2007; CSIRO, 2011). By 2070, Adelaide may experience double the number of days over 35°C compared to the long-term average (CSIRO and BoM, 2007; CSIRO, 2011).

Increasing temperatures are likely to influence both wine grape production and quality across Australian wine regions, including McLaren Vale and the Barossa Valley (Webb et al., 2007; CSIRO, 2011; Lereboullet et al., 2013).

Between 25,200 and 43,000 residential buildings may be at risk of inundation from a sea-level rise of 1.1 m (DCC, 2009). The estimated replacement value of these residential buildings is between $4.4 billion and $7.4 billion (DCC, 2009).

Availability of water for dryland and irrigated agriculture around Adelaide and the Mount Lofty Ranges is expected to decline (Bardsley and Sweeney, 2010; Heneker and Cresswell, 2010).

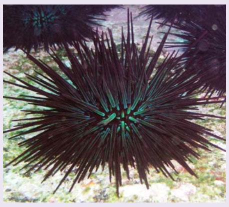
Birds confined to southern South Australia (particularly Kangaroo Island) are among those most likely in Australia to lose climatically suitable habitat in the future (Garnett et al., 2013).

Kangaroo Island is likely to experience an increase in annual average temperature between 0.45°C and 1.3°C by 2030 (DENR, 2010).

**Image sources (clockwise from top).** Hot days in Adelaide: Bogers/Flickr; Vineyard in Barossa Valley: Michael Dawes/Flickr; Kangaroo Island Temperature: Navin75/Flickr.

# TASMANIA

**Population:** 512,200
**Capital:** Hobart
**Area:** 68,401 km$^2$



Increasing sea temperatures and a strengthening of the East Australian Current has extended the range of the long-spined sea urchin into Tasmanian waters, damaging kelp beds and Tasmanian rock lobster habitat (Pecl et al., 2009; Banks et al., 2010).

Average temperature is expected to rise by between 1.6°C and 2.9°C over the 21$^{st}$ century; this is less than the expected increase in global average temperature (Grose et al., 2010).

A one-in-100 year high sea-level event, based on late 20th century conditions, could occur as frequently as more than once per year to every six years by 2100, depending on average sea-level rise (McInnes et al., 2011).

As temperatures warm into the 21st century, Tasmania is expected to experience less temperature related deaths, due to a decrease in cold-related deaths (Bambrick et al., 2008).

While total statewide annual rainfall is not projected to change markedly by the end of the century, significant regional trends may occur. Rainfall over central Tasmania is expected to decrease in all seasons. The east of the state is expected to experience an increase in rainfall, predominantly in summer and autumn. West coast summer rainfall is expected to decrease, while west coast winter rainfall is expected to increase (Bennett et al., 2010).

The incidence of frost is expected to decline substantially by the end of the century, with many sites likely to experience less than half the current number of frosts (Holz et al., 2010).

The Tasmanian wilderness is vulnerable to increasing temperatures, sea-level rise, extreme weather events, changing fire regimes and reduction in snow cover (ANU, 2009). These changes are likely to affect the wilderness in numerous ways including:

- Changing elevation of the treeline from about 250 m to 300 m above present;
- Fires threatening alpine and rainforest vegetation and buttongrass moors; and
- Erosion particularly in the Central Plateau and around coastlines (ANU, 2009).

Climate change is reducing the area of climatically suitable habitat for many plants and animals in the state, many of which have limited ability to adapt to rapid change. For example, birds living on King Island (Garnett et al., 2013), moorland fauna such as the broad-tooth mouse (DPIPWE, 2010) and iconic tree species such as King Billy pines (ANU, 2009) are likely to lose climatically suitable habitat.

**Image sources (clockwise from top).** Long-spined sea urchin: Scott Ling; Broad-toothed mouse: Michael Driessen; King Billy pines: Prescott/Flickr; Storm damage at Clarence City Council: Dr Tom Shand, UNSW Water Research Laboratory.

# VICTORIA

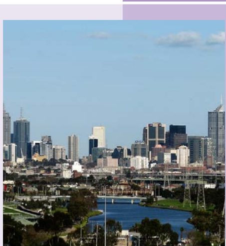
**Population:** 5,649,100
**Capital:** Melbourne
**Area:** 227,416 km²

The southern Murray-Darling Basin and Victoria will, on average, be drier in the future (CSIRO, 2012). This rainfall decline is expected to occur in winter, translating to a considerable reduction in winter and annual runoff (CSIRO, 2012).

An increase in dangerous fire weather is expected for southeast Australia (Clarke et al., 2011).

Declines in snow cover in the Australian alpine region are expected to continue. Areas with an average annual snow cover of at least 30 days per year could decline between 30% and 93% by 2050, relative to 1990 (Hennessey et al., 2008b). The worst case scenario is the complete loss of the alpine zone during this century.

The average long-term stream flow into Melbourne's water supply catchments is estimated to decline 10% by 2030 (CSIRO, 2012).



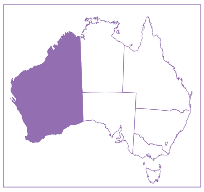
Average temperature in Melbourne is expected to increase by between 0.6°C and 1.2°C by 2030 compared to 1990 levels (CSIRO and BoM, 2007; CSIRO, 2011). Melbourne may experience a doubling of the number of days over 35°C by 2070 compared to the long-term average (CSIRO and BoM, 2007; CSIRO, 2011).

The Gippsland Lakes, including Ninety Mile Beach and Corner Inlet, represent one of the most vulnerable coastal areas in Australia (DCC, 2009). The region is already vulnerable to flooding, but rising sea levels could exacerbate this vulnerability. Within 50 years, parts of the Gippsland coast will be inundated to an extent requiring protection or relocation of assets including dwellings and commercial buildings (Gippsland Coastal Board, 2008).

An estimated 27,600 to 44,600 residential buildings may be at risk of inundation from a sea-level rise of 1.1 m and storm tides associated with a one-in-100 year storm (DCC, 2009).

**Image sources (clockwise from top).** Australian Alps: alistercoyne/Flickr; Gippsland Lakes: Heikof/Flickr. Melbourne skyline: Klomiz/Flickr; Murray-Darling Basin: Storer Boat Plans/Flickr.

# WESTERN AUSTRALIA



**Population:** 2,451,400
**Capital:** Perth
**Area:** 2,529,875 km²


The value of existing road infrastructure at risk of a sea-level rise of 1.1 m is higher than any other state, with between 7,500 and 9,100 km exposed (DCCEE, 2011).

The world famous Ningaloo Reef, like other coral reefs, is highly sensitive to climate change. A marine heatwave in 2011 caused the first-ever reported bleaching at Ningaloo Reef (Wernberg et al., 2013). The Reef, and the multi-million dollar tourism industry it supports, face significant long term risks from a changing climate.

Up to 2,100 commercial buildings – the highest number for any state in Australia – would be threatened by a 1.1 m sea-level rise (DCCEE, 2011).

Modelling of impacts on local plants (such as banksias) and animals (such as the quokka) consistently indicates that their available habitat may become significantly reduced as the climate changes (Fitzpatrick et al., 2008; Gibson et al., 2010; Yates et al., 2010).

World Heritage-listed Shark Bay is likely to experience higher sea water temperatures, rising sea levels, ocean acidification, more intense storms and cyclone activity and more frequent droughts (ANU, 2009). These changes are likely to alter seagrass habitats, shift distributions of marine life and change relationships between sharks and other marine species (ANU, 2009).

By 2030, annual average temperatures is projected to increase by up to 1°C in southern and coastal areas and up to 1.5°C inland (CSIRO and BoM, 2007).

A continued decline in average annual rainfall in the southwest is expected (CSIRO and BoM, 2007; IOCI, 2012). Median stream flow in southwest Western Australia is estimated to decline 25% by 2030 (CSIRO, 2012b).

**Image sources (clockwise from top).** Ningaloo Reef: oemebamo/Flickr; Quokka: Chris Jervis/Flickr; Coastal roads: Yewenyi/Flickr; Shark Bay: Jason Means/Flickr.

# CHAPTER 4: CLIMATE CHANGE: THE SCIENCE-POLICY INTERFACE

Climate change is much more than just an environmental problem. It is an economic, technological and social challenge of such a scale that it requires a fundamental transformation of our societies, in particular our means of generating energy, if we are to stabilise the climate at a level that is safe for future generations. Science has a strong, ongoing role to play in underpinning the many decisions that societies are already making and will need to make in the future to ensure this transformation occurs in an effective, timely and socially acceptable fashion. This section describes how our scientific understanding of the nature of climate change and the risks that it poses can help us to determine what constitutes 'dangerous' climate change, assess the magnitude and urgency of the emissions reduction task, and manage the carbon cycle in the best way possible.

## 4.1 Defining dangerous climate change

There is an inevitable trade-off between 'mitigation' – actions to slow and then stop the human-driven changes to the climate system – and 'adaptation' – learning to live with a changing climate. At the heart of this trade-off is a judgment about what constitutes 'dangerous' climate change, the point beyond which the risks of climate change to our well-being are unacceptably high. Although determining where dangerous climate change lies is indeed ultimately a value judgment by societies, science has a strong role to play in informing that decision.

One of the most widely used approaches towards marshaling scientific knowledge to support the debate about dangerous climate change is the 'reasons for concern' assessment developed for the IPCC's Third Assessment Report in 2001. *Figure 48* shows this assessment, sometimes called the 'burning embers diagram,' and an update for 2009 using the same methodology (Smith et al., 2001; 2009).

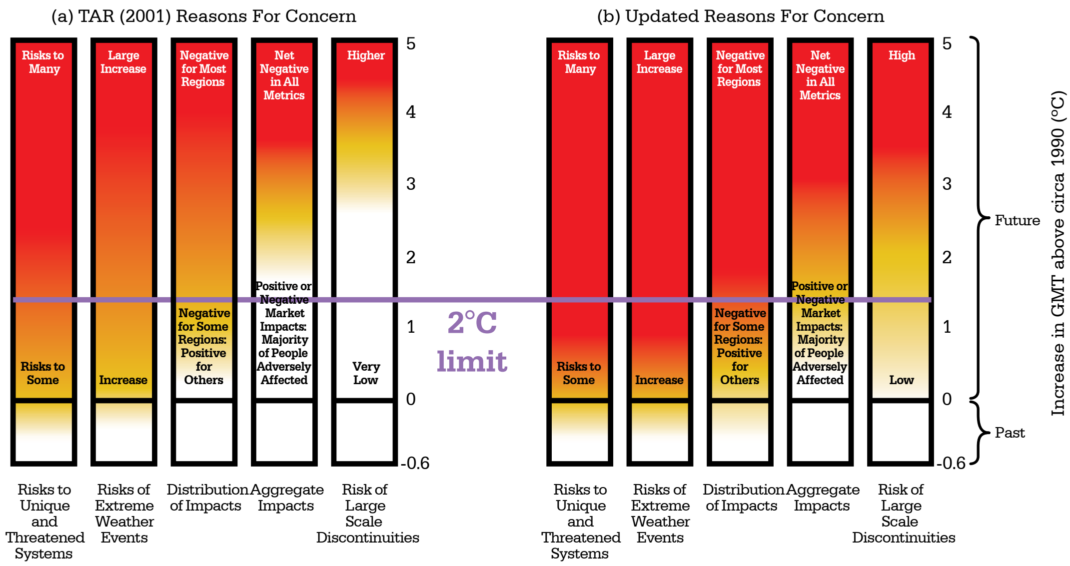



**Figure 48:** Risks from climate change by reason for concern (RFC) for 2001 compared with updated data. Climate change consequences are plotted against increases in global mean temperature (GMT) (°C) after 1990. Each column corresponds to a specific RFC and represents additional outcomes associated with increasing global mean temperature. The colour scheme represents progressively increasing levels of risk. The historical period 1900 to 2000 warmed by about 0.6°C, which led to some impacts. (A) RFCs from the IPCC Third Assessment Report as described in Smith et al., 2001. (B) Updated RFCs derived from IPCC Fourth Assessment Report as discussed in Smith et al., 2009.

The approach focuses on a number of broad areas where climate change poses significant risks or potential impacts, and relates the severity of the risk to the level of climate change, using global average air temperature as an indicator. The assessment includes the risks to natural ecosystems, the risks posed by extreme weather events (*Section 3.1*), and risk of crossing tipping elements in the climate system (*Section 2.3*; called 'large-scale discontinuities' in the figure). The intensity of the colours represents the severity of the risks, with the deep red colours at the top of the diagram representing very severe risks. The so-called 2°C limit, accepted by most nations of the world as an estimate of the level beyond which dangerous climate change lies, is superimposed on the figure.

Several features stand out in the figure. First, as our knowledge of the risks associated with climate change improves, the estimated severity of the risks for a given level of global average temperature rise has increased. That is, more serious impacts are now expected to occur at lower levels of climate change.

Second, according to the 2009 assessment of the reasons for concern, the 2°C limit no longer appears to be so appropriate as a dividing line above which climate change can be considered 'dangerous'. Our more recent understanding suggests that quite severe impacts can occur in several of these areas below a 2°C rise in temperature. There is also a risk that some of the tipping points in the climate system could be crossed by the time a temperature rise of 2°C is reached. It is partly for this reason that the small island states, countries that are very vulnerable to climate change, have not accepted the 2°C limit and have instead recommended that the rise in global average temperature be limited to no more than 1.5°C (UNFCCC, 2008; AOSIS, 2013).

Because of the inertia of the climate system, ongoing warming of the atmosphere is already committed for several decades into the future, even if fossil fuel burning were to cease today. This means that any action to keep global warming below the 1.5°C or 2°C limit needs to occur many decades before

those warming values are reached. Just like turning around a battleship, we cannot turn around the increase in temperature immediately. Current estimates of committed warming are in the range 0.3-0.9°C above the 0.8°C increase that has already been observed (IPCC, 2007). To avoid crossing the 1.5-2°C warming limits, immediate action is required to reduce $CO_2$ emissions. Turning around the battleship we must start turning the wheel now. Any delay in turning the wheel just means that the battleship gets closer to danger and it becomes more and more difficult to avert the danger.

Finally, at the current level of climate change – a rise of 0.8°C in global average temperature – some impacts of climate change are already noticeable, especially in some natural ecosystems and in the severity and frequency of some extreme weather events. Indeed, as described in the previous section, these types of impacts are already being observed across Australia and the world.

In a broader sense, the trade-off between mitigation and adaptation is often posed in a cost-benefit framework. However, many such analyses are highly skewed, with the present-day costs often prioritised over the costs imposed on future generations. Furthermore, non-economic costs, such as those associated with the impacts on individual health and well-being and the resilience of societies, are ignored or downplayed as they tend to be difficult to quantify in monetary terms. There still remain daunting uncertainties around the costs – both economic and non-economic – of climate change impacts or, more importantly, the costs of failing to adapt effectively. In addition, the benefits of effective mitigation are generally not adequately incorporated; these include cleaner and more resilient energy systems; more energy efficient buildings; and faster, more convenient and less polluting transport.

## 4.2 The magnitude of the task: targets, timetables and budgets

Adopting the 2°C limit allows us to assess the magnitude of the emissions reductions that are required to achieve this goal. The most commonly used approach to determining the policies needed to meet the 2°C limit is based on the so-called 'targets and timetables' approach. It is a complex approach, and prone to much confusion.

At its most fundamental level, the approach works like this. An estimated concentration of greenhouse gases that would lead to a 2°C temperature rise is calculated. This is done through multiple simulations by global climate models of the response of the climate to various levels of greenhouse gas concentrations. The emission reductions required to stabilise the concentration of greenhouse gases at the target level are then estimated. Countries then set emission reduction targets and the timetables to achieve them as their contribution to the global effort to reduce greenhouse gas emissions. Countries' progress against their targets can be tracked over time through estimates of changes in national emissions.

Each nation's commitments can vary in several ways, namely:

- the greenhouse gases included
- the baseline year against which the percentage reduction is to be applied
- whether the percentage reduction applies to actual emissions or to the 'emission intensity' of the economy
- whether the reductions are applied against a business-as-usual or some other future scenario.

It takes some very complicated calculations to determine what the aggregate of these very differently formulated policies actually mean in terms of the amount of greenhouse gases in the atmosphere.

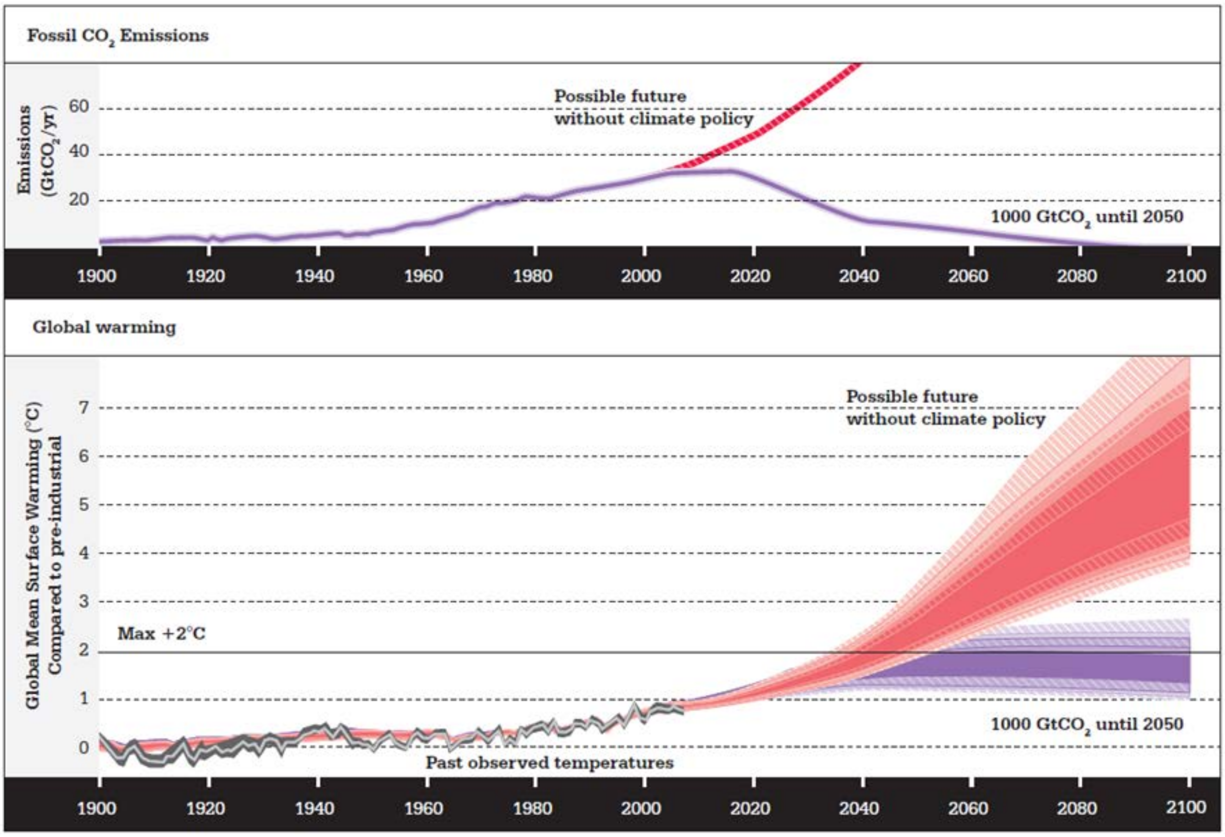



**Figure 49:** Top: Fossil fuel $CO_2$ emissions for two scenarios: one 'business as usual' (red) and the other with net emissions peaking before 2020 and then reducing sharply to near zero emissions by 2100, with the cumulative emission between 2000 and 2050 capped at 1,000 billion tonnes of $CO_2$ (blue). Bottom: Median projections and uncertainties of global-mean surface air temperature based on these two emissions scenarios out to 2100. The darkest shaded range for each scenario indicates the most likely temperature rise (50% of simulations fall within this range).

**Source:** Australian Academy of Science, adapted from Meinshausen et al., 2009

A much simpler and more robust approach to track global progress has been developed by scientists to cut through this mass of confusion. Usually called the budget approach, it simply links the projected rise in temperature directly to the total global emissions of $CO_2$ over a given period of time, regardless of national source (Meinshausen et al., 2009; Allen et al., 2009; *Figure 49*). The relationship between emissions and rise in temperature is probabilistic because of the uncertainty around the sensitivity of the climate to a given amount of greenhouse gas emissions (Raupach et al., 2011; see *Section 2.5*).

For a 75% chance of limiting global temperature rise to 2°C, we can emit no more than 1,000 billion tonnes of $CO_2$ from 2000 to 2050. That seems like a very large number, but we are already 13 years into that period so we can check on progress against the overall budget (*Figure 50*). The figures, available for the 2000-2011 period and projected for 2012, are not encouraging. In 2000 fossil fuel emissions were 24.8 billion tonnes of $CO_2$, and emissions rose to 34.7 billion tonnes in 2011 (GCP, 2012). Another 35.6 billion tonnes is projected for 2012. This brings the total for the 13-year period to 391.0 billion tonnes, nearly 40% of the total allowable budget (CDIAC, 2013). That leaves a budget of just over 600 billion tonnes of $CO_2$ for the next 35-40 years, after which the world economy needs to be completely decarbonised. Under a business-as-usual model, with emissions growing at 2.5% per annum, we are on track to have

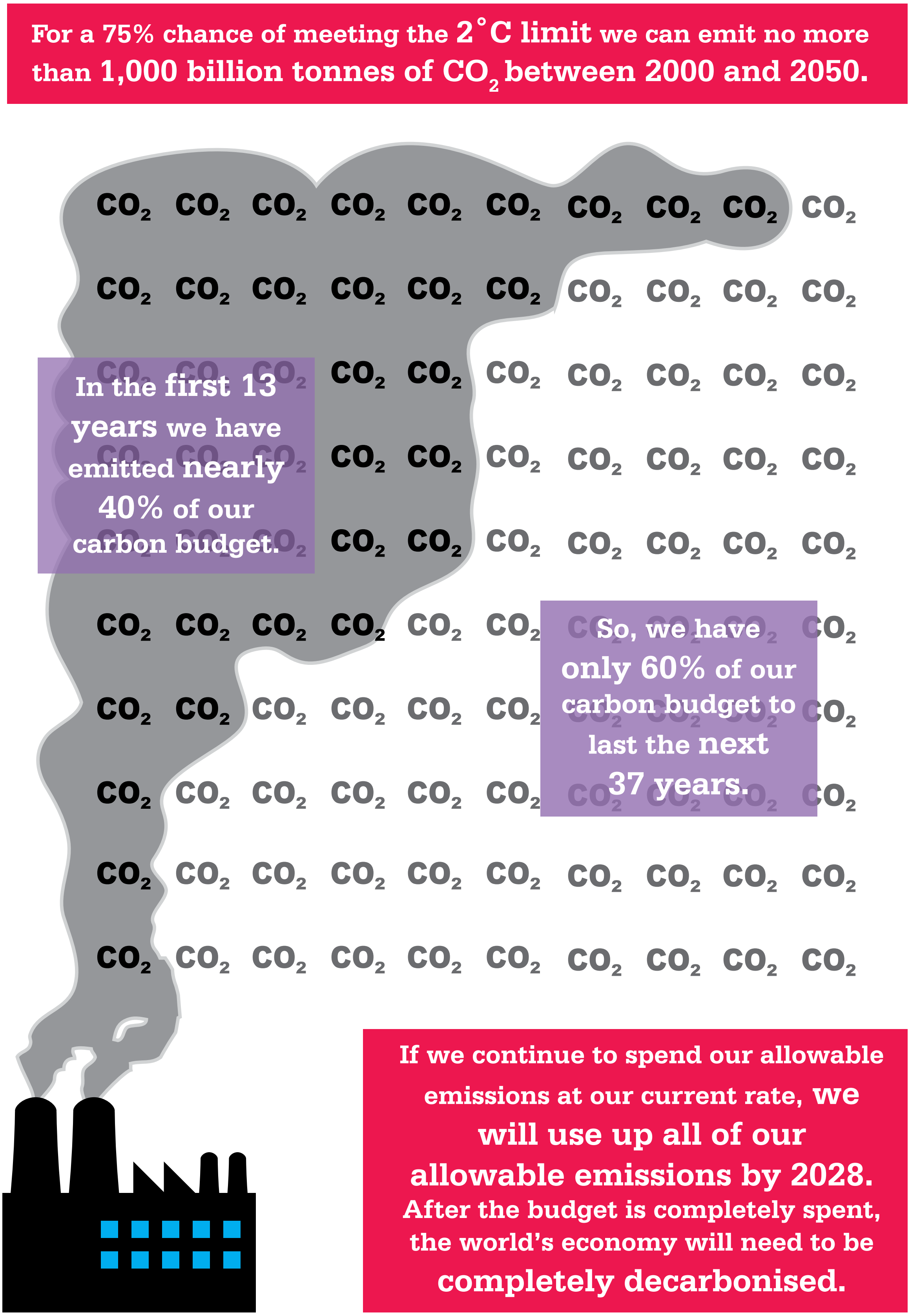



**Figure 50:** Overspend in the carbon budget. Each $CO_2$ symbol represents 10 billion tonnes of $CO_2$.

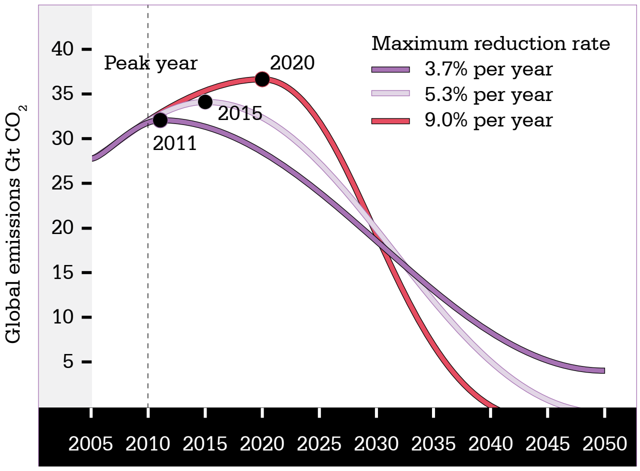



**Figure 51:** Three emission trajectories based on the budget approach and giving a 67% probability of meeting the 2°C limit.

Source: WBGU, 2009

completely used up the allowable global emissions within the next 16 years, that is, by 2028.

The possible emission trajectories for achieving decarbonisation of the world's economy in time and within budget to meet the 2°C limit are shown in *Figure 51*. How quickly we must reduce emissions is closely related to when emissions 'peak,' that is when they are at the highest levels. In 2013 emissions are still rising by about 3% per year, so they are still on a strongly upward trajectory. If emissions could somehow peak in 2015, just two years away, the maximum rate of emission reductions thereafter would be 5.3%, a very daunting task. However, if we allow emissions to continue to rise through the rest of this decade and don't reach the peaking year until 2020, the maximum rate of emission reductions thereafter is 9%, a virtually impossible task unless economies around the world prioritise emission reductions above all other economic and technological goals.

Targets and timetables provide a way to define and track commitments for reducing emissions, but do not provide a strong and clear link to the overall task. The budget approach provides simplicity and transparency, and has an additional, very important advantage – it focuses attention away from interim emission reduction targets such as those for 2020 and squarely on the end game – the decarbonisation of the world's economies by mid-century.

## 4.3 The carbon bubble

Over recent years there has been a resurgence in the discovery and exploitation of new reserves of fossil fuels in Australia and elsewhere, with the prospect of new coal fields being developed and non-conventional sources such as coal-seam gas and shale oil being exploited. But how does this rapid increase of new and non-conventional fossil fuel reserves stack up against the budget approach to emission reductions? The answer is sobering (Carbon Tracker and the Grantham Research Institute, 2013).

The current amount of carbon embedded in the world's indicated fossil fuel reserves (coal, oil and gas) would, if all were burned, emit an estimated 2,860 billion tonnes of $CO_2$ (IEA, 2012). This is nearly five times the allowable budget of about 600 billion tonnes to stay within the 2°C limit.

There are some limited ways in which the budget could be extended. The amount of fossil fuels that could be burned could be extended to an equivalent of 900 billion tonnes of $CO_2$ if the emissions of other greenhouse gases, such as methane and nitrogen oxide, were vigorously reduced over the coming decades. This is because methane and nitrogen oxide are potent greenhouse gases, although $CO_2$ is the most important one (*Figure 7*). The most optimistic estimate of the deployment of carbon capture and storage technology could extend the budget to 2050 by another 125 billion tonnes of $CO_2$ emissions (Carbon Tracker and the Grantham Research Institute, 2013). That gives a total, under the most optimistic assumptions, of 1,025 billion tonnes of $CO_2$ that could be emitted from fossil fuels, still only about 35% of the world's reserves.

Lord Stern, one of the world's most respected economists in the climate change arena, warned investors that most of the world's fossil fuel reserves are essentially unburnable as the need to reduce emissions becomes ever more apparent. He said "They (smart investors) can see that investing in companies that rely solely or heavily on constantly replenishing reserves of fossil fuels is becoming a very risky decision" (Carbon Tracker and the Grantham Research Institute, 2013).

Again, the budget approach to emission reductions provides exceptional clarity in analysing the carbon bubble. Major changes to the ways in which energy is produced are needed, and most of the world's known fossil fuel reserves will have to be left in the ground if the world is serious about respecting the 2°C limit. Increasing fossil fuel emissions are largely from burning of coal, which also constitutes the majority of potential emissions from fossil fuel reserves (IEA, 2012). Australia's coal reserves alone represent about 51 billion tonnes of potential $CO_2$ emissions, or around one twelfth of the 600 billion tonne global budget (Carbon Tracker and The Climate Institute, 2013). Growth in the use of coal will need to be turned around, so that it makes up a much smaller proportion of the global energy mix and eventually not used at all.

## 4.4 Managing the carbon cycle

Most of the efforts to stabilise the climate system involve management of various parts of the carbon cycle, so it is important to understand how the carbon cycle works and what are the most effective points of intervention.

*Figure 52* shows the human-driven changes to the global carbon budget over the past 50 years (Le Quéré et al., 2013). The components above the horizontal line represent emissions to the atmosphere of $CO_2$ from human activities – fossil fuel combustion, cement production and land-use change. Emissions are dominated by fossil fuel emissions, and by 2010 they accounted for over 90% of total emissions.

The components below the horizontal line show where the carbon emissions go, the so-called 'sinks'. Slightly less than half of the carbon emitted by human activities stays in the atmosphere; since 1959 the average has been 44%. The other 56% is stored approximately equally in the land and the ocean. There is much more variability in the strength of the land sink from year-to-year than in the ocean sink, and this variability is reflected in the atmosphere also.

So far the land and ocean sinks have kept pace proportionately with the emissions from fossil fuel combustion. This 'service' in the climate system has been important in limiting the rise in the atmospheric $CO_2$ concentration. But we cannot assume that the strength of these sinks will increase or even remain constant as emissions continue to rise. Our best understanding of the processes that control the land and ocean sinks suggest that the sinks will eventually weaken or possibly even turn into sources of carbon back to the atmosphere (Friedlingstein et al., 2006), but that this is not likely to happen until the global average temperature rises more than 2°C above the pre-industrial level. This and the need to reduce ongoing carbon emissions from land use and to avoid the activation of new emissions of carbon from natural systems (*Section 2.3*) is another strong argument for observing the 2°C limit.

In designing strategies to reduce emissions or increase uptake of carbon in the ocean and land sinks, it is important to understand the difference between carbon emissions from fossil fuel combustion and those from land-use change (Mackey et al., 2013). Carbon emissions from land-use change, primarily from deforestation, forest degradation and tillage practices, represent a redistribution of carbon in the active land-atmosphere-ocean cycle. No 'new' carbon is introduced to this cycle. Carbon can be taken up again from

the atmosphere – that is, redistributed back from the atmosphere to the land – but there are limits to this amount, determined by the prevailing environmental conditions.

The combustion of fossil fuels represents the addition of new carbon into the active land-atmosphere-ocean system, carbon that has been locked away from the active cycle for millions of years. As shown in *Figure 52*, the active carbon cycle redistributes this additional carbon among the land, ocean and atmospheric sinks. Optimistic estimates show that the potential amount of carbon that the land can take up is much less than the amount that has been released from fossil fuel combustion, let alone the additional amounts that continue to be released from that source (Mackey et al., 2013).

The implication for climate policy of these basic features of the carbon cycle is clear. Storing carbon in land systems cannot 'offset' fossil fuel emissions. Storing carbon in land systems is nevertheless a positive action, but for different reasons. It returns 'legacy carbon' that was originally emitted from the land to the atmosphere, and it can have a number of important co-benefits, such as increasing the productivity of agricultural systems and providing species habitats in reforested lands. However, using such activities as 'offsets' for fossil fuel emissions can actually be counterproductive by allowing the continual addition of new carbon into the active cycle. The climate can only be stabilised if the addition of new carbon from fossil sources is eliminated – that is, if the global economy is decarbonised – and the amount of carbon cycling through the active land-atmosphere-ocean system ceases to increase.

STORING CARBON IN LAND SYSTEMS CANNOT 'OFFSET' FOSSIL FUEL EMISSIONS. STORING CARBON IN LAND SYSTEMS IS NEVERTHELESS A POSITIVE ACTION, BUT FOR DIFFERENT REASONS.

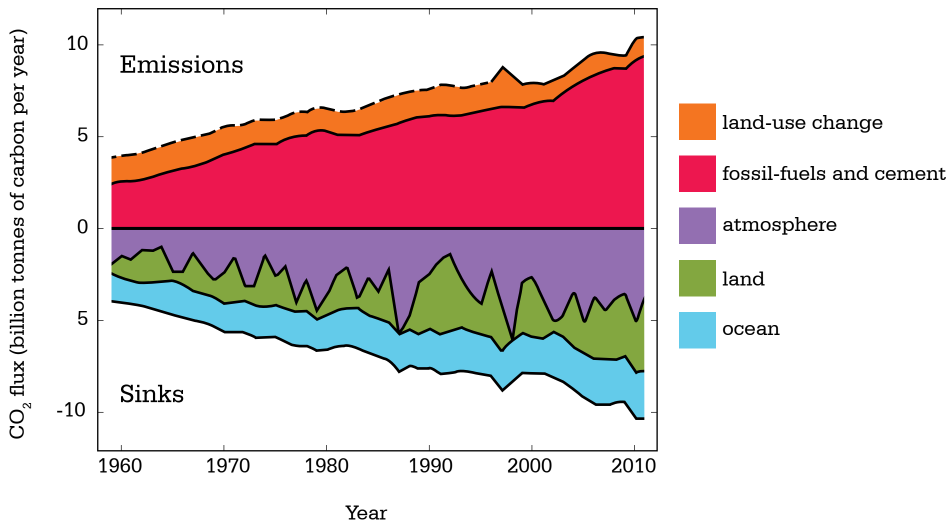



**Figure 52:** The global carbon budget from 1959 to 2011. Components above the horizontal zero line are emissions to the atmosphere and components below the line show where the emissions are stored in the carbon cycle. The dashed land-use change line does not include management-climate interactions. The units of the vertical axis are equivalent to billion tonnes of carbon per year.

**Source:** Le Quéré et al., 2013

## 4.5 This is the critical decade

The scientific basis for urgent action on climate change is set out clearly in this report.

The climate is warming, and many other changes to the climate system – patterns of precipitation, sea-level rise, melting ice, acidification of the ocean – are also occurring. It is beyond reasonable doubt that the emission of greenhouse gases by human activities, mainly carbon dioxide from the combustion of fossil fuels, is the primary cause for the changes in climate over the past half-century.

The impacts of climate change can already be observed. Heatwaves have become longer and hotter. High bushfire danger weather has increased in southeast Australia. Heavy rainfall events are increasing, while the southeast and southwest corners of the continent have become drier. The rise in global sea level is increasing the incidence of coastal flooding.

Analyses of these observed impacts and the impacts projected for future levels of climate change have convinced nations that the global average temperature, now at 0.8°C above the pre-industrial level, must not be allowed to rise beyond 2°C above pre-industrial – the so-called 2°C limit. Societies will have to adapt to even more serious impacts as the temperature rises towards the 2°C limit, but ensuring that this limit is not crossed will prevent even worse impacts from occurring, including the crossing of tipping points that could drive the warming trend out of human control.

To have a good chance of staying within the 2°C limit, we can emit no more than 1,000 billion tonnes of $CO_2$ from 2000 to mid-century. In the first 13 years of this period, we have already emitted nearly 400 billion tonnes, about 40% of the budget.

Worse yet, the rate at which we are spending the budget is still much too high, and growing. For example, from 2011 to 2012, global $CO_2$ emissions rose by 2.6%.

There are some promising signs that the first steps are being taken towards decarbonising the global economy. Renewable energy technologies are being installed at increasing rates in many nations. The world's biggest emitters – China and the United States – are beginning to take meaningful actions to limit and reduce emissions (for further information see the Climate Commission's *The Critical Decade: Global action building on climate change*). However, the rapid consumption of the carbon budget, not to mention the discovery of many new fossil fuel reserves, highlights the enormity of the task. Much more needs to be done to reduce emissions… and quickly.

The carbon budget is clear and compelling. To stay within the 2°C limit, the trend of increasing global emissions must be slowed and halted in the next few years and emissions must be trending downwards by 2020 at the latest. Investments in and installations of renewable energy must therefore increase rapidly. And, critically, most of the known fossil fuel reserves must remain in the ground.

**THIS IS THE CRITICAL DECADE TO GET ON WITH THE JOB.**

# GLOSSARY

### Adaptation

The steps governments, businesses, communities and individuals take to deal with risks from climate change impacts.

### Aerosols

Small particles or liquid droplets in the atmosphere that can absorb or reflect sunlight, depending on their composition. Aerosols may be either natural or anthropogenic. They have a net cooling effect on the climate.

### Anthropogenic

Resulting from or produced by human activities.

### Atmospheric circulation

The large-scale movement of air through which heat and moisture are distributed around the Earth. It includes winds, jet streams and large global weather patterns.

### Biome

A large community of plants and animals that occupies a distinct region and which is usually characterised by the dominant vegetation and climate. Examples include tropical rainforest, desert, tundra and grassland.

### Budget approach

An approach to estimating required greenhouse gas emission reductions that directly links the projected rise in temperature to aggregated global emissions for a specified period, usually 2000 to 2050 or 2000 to 2100. For example, humanity can emit no more than 1,000 billion tonnes of $CO_2$ between 2000 and 2050 to have a probability of about 75% of limiting temperature rise to 2°C or less above pre-industrial levels. The budget approach does not stipulate any particular trajectory or method to reduce emissions, so long as the overall budget is respected.

### Business-as-usual

Scenarios where no changes to current policies are taken to limit greenhouse gas emissions further. In these scenarios, greenhouse gas emissions continue to rise strongly through the 21st century.

### Calving

A sudden breaking away of a mass of ice from the edge of the ice sheet.

### Carbon dioxide ($CO_2$)

A gas that occurs naturally and which is also a by-product of fossil fuel combustion and other industrial processes, and from biomass burning and some types of land-use change. $CO_2$ is the main anthropogenic greenhouse gas that affects the climate.

### Carbon dioxide fertilisation

Plants require $CO_2$ for photosynthesis and growth. Increased atmospheric $CO_2$ concentration can enhance growth in some plant species as there is more $CO_2$ available for growth. This is the carbon dioxide fertilisation effect. However, if water or nutrient availability is limited there may be little or no enhancement of plant growth.

### Carbon sink

Reservoirs such as forests and oceans absorb and release carbon, and become a carbon sink when the amount absorbed is greater than the amount released.

### Carbon sequestration

The removal and storage of carbon dioxide from the atmosphere by plants, soils or technological measures.

### Climate change

Any significant change in the measures of climate lasting for several decades or longer, including changes in temperature, precipitation, or wind patterns. Historically, the Earth's climate has changed over time but it is widely agreed the recent observed changes, over the past 50 years or so, have been primarily caused by human activities.

### Climate feedbacks

The influence of one climate-related process on another that in turn influences the original process. Feedbacks can be positive (reinforcing the original process) or negative (dampening the original process). An example of a positive feedback is where increased temperature leads to a decrease in ice cover, which in turn leads to a decrease in reflected radiation and therefore a further increase in temperature.

### Climate model

A mathematical representation of the climate system that is based on the physical, chemical, and biological properties and processes of the climate system. Climate models are applied as a research tool to better understand the behaviour of the climate in the past, present and future. They are often used to simulate possible future changes in climate.

### Climate sensitivity (or, equilibrium climate sensitivity)

In general, equilibrium climate sensitivity expresses the relationship between a change in radiative forcing and the response of the climate system once the system has reached a new equilibrium after the imposition of the change in radiative forcing. Specifically, the term is often defined as how much the average global surface temperature will increase if there is a doubling of $CO_2$ in the air compared to pre-industrial level (i.e. from 280 to 560 ppm), once the planet has had a chance to settle into a new equilibrium after the increase in $CO_2$ occurs.

### Coastal inundation (or coastal flooding)

Sometimes called a 'high sea-level event,' coastal inundation is the flooding of coastal areas as a result of wind-driven waves or a storm surge and is often exacerbated by a high tide. These events become more frequent as a result of rises in sea level.

### Confidence

Refers to the validity of a finding, based on the type, amount, quality, and consistency of evidence and on the level of agreement. The IPCC uses a range of different levels of confidence: very low, low, medium, high, and very high, and has specific definitions of each of these levels. The level of confidence increases with increasing evidence and agreement.

Also see *Uncertainty*.

# GLOSSARY

## Cryosphere

Parts of the Earth System where water freezes for at least part of the year, including ice caps, ice sheets and glaciers on continents, sea ice, ice shelves, snow, river and lake ice and frozen ground (permafrost). Its largest components by mass are the ice sheets in Greenland and Antarctica.

## Drought

A period of abnormally long dry weather compared to the normal pattern of rainfall. Drought can be considered as an 'agricultural drought', when insufficient soil moisture negatively affects crop production; a 'hydrological drought', when stream flow, lake levels or groundwater levels drop to a sufficiently low level; or a 'meteorological drought', when there is a period of insufficient rainfall compared to a long-term average. The meteorological definition of drought is most relevant for discussing the relationship between climate change and drought.

## Ecosystems

All living organisms in an area as well as their physical environment, functioning together as a unit or single system.

## Emission intensity (economic)

The amount of emissions per unit of economic output, e.g. tonnes of $CO_2$ relative to gross domestic product.

## Emissions scenario

A representation of future greenhouse gas emissions based on assumptions about driving forces (such as actions taken to reduce greenhouse gas emissions, technological change, demographic and socioeconomic development). Emissions scenarios may be described as high, medium, low, business-as-usual, or specific scenarios based on a defined set of assumptions. Emissions scenarios are used in climate models to generate projections of how the climate will respond to a given emission scenario.

## Energy balance

The difference between the total amount of energy coming into the Earth System and outgoing energy. If this is positive, warming occurs; if it is negative, cooling occurs. For a stable climate, averaged over the globe and over long time periods, the energy balance must be neutral (not positive or negative). Because the climate system derives virtually all its energy from the sun, neutral balance implies that, globally, the amount of incoming solar radiation on average must be equal to the sum of the outgoing reflected solar radiation and the outgoing thermal infrared radiation. An influence on this balance, be it driven by human activity or natural, is called 'radiative forcing.'

## Evaporation

The change of a substance from a liquid to a gas.

## Evapotranspiration

The term is normally applied to land systems, and refers to the combined processes of evaporation from the surface of the soil and transpiration from vegetation. Transpiration is the loss of water from plants to the atmosphere through the evaporation of moisture from leaves and stems.

## Exposure

The presence of people, infrastructure or ecosystems in places that could be subject to an influence, in this case climate change.

### Extreme weather events

A weather or climate event that is unusually intense or long, occasionally beyond what has been experienced before. Examples include very high (and low) temperatures, very heavy rainfall (and snowfall in cold climates), droughts and tropical cyclones. By definition, extreme events occur only rarely, and they are noticeable because they are so different from the usual weather and climate, and because they are associated with adverse impacts on humans, infrastructure and ecosystems.

### Fossil fuels

A general term for crude oil and its products, coal, natural gas or heavy oils. Fossil fuels were formed from decayed plants and animals exposed to heat and pressure in the Earth's crust over hundreds of millions of years.

### Greenhouse gases

Gases that absorb some of the heat energy emitted from the Earth's surface and cause the greenhouse effect. Water vapour ($H_2O$), carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), methane ($CH_4$), and ozone ($O_3$) are the primary greenhouse gases in the Earth's atmosphere. Carbon dioxide is the most important of the long-lived greenhouse gases, that is, the gases that remain in the atmosphere for decades, centuries, or millennia.

### Heatwave

A period of at least three days where the combined effect of high temperatures and excess heat is unusual within the local climate. Excess heat often occurs when unusually high overnight temperatures also occur, Heatwaves are relative to the average conditions of the local climate.

### Heavy rainfall

A heavy rainfall event is a deluge of rain that is much longer and/or more intense than the average conditions experienced at a particular location. It is relative to the average conditions of the local climate.

### Ice sheet

A layer of ice covering a large area (50,000 square kilometres or more). Ice sheets form through the accumulation of thousands or millions of years of snowfall, followed by compression of the snow as the weight of new snow presses down on the previous year's fall.

### Methane

A greenhouse gas with approximately 25 times the warming capacity of $CO_2$ on a molecule-per-molecule basis, when measured over a timeframe of 100 years. Methane occurs naturally and is also produced through anaerobic (without oxygen) decomposition of waste in landfills, animal digestion, decomposition of animal wastes, production and distribution of natural gas and petroleum, coal production, and incomplete fossil fuel combustion. Methane has a much shorter lifetime in the atmosphere than $CO_2$ and is present in lower concentrations.

### Mitigation

Climate change mitigation includes actions taken globally, nationally and individually to limit changes in the global climate caused by human activities. Mitigation activities are designed to reduce greenhouse emissions and/or increase the amount of greenhouse gases removed from the atmosphere.

# GLOSSARY

## Nitrous oxide

A greenhouse gas nearly 300 times more potent than $CO_2$ on a molecule-per-molecule basis, when measured over a period of 100 years. Nitrous oxide occurs naturally when bacteria breaks down nitrogen in soils and the ocean. It is also produced through the use of nitrogenous fertilisers, fossil fuel combustion, nitric acid production, and biomass burning. Nitrous oxide is present in the atmosphere in much lower concentrations than $CO_2$.

## Ocean acidification

Occurs when oceans absorb additional $CO_2$ from the atmosphere. This absorption affects ocean chemistry because $CO_2$ reacts with seawater to form carbonic acid, thus increasing the acidity of the ocean. Increased acidity reduces availability of carbonate ions (charged particles), which calcifying marine organisms use to maintain or build exoskeletons and shells.

## Ocean circulation

The large-scale movement of water by which heat is distributed through the oceans. The movement of water around the oceans has two parts which are strongly linked: density-driven circulation and wind-driven circulation. Density-driven circulation is due to differences in the density of seawater at different locations. The density of seawater depends on its temperature and its salinity. Wind-driven circulation is a result of the force of winds on the ocean surface. Winds give momentum to the surface layer of the ocean creating surface currents and circulation.

## Parts per million (ppm)

A way of expressing dilute concentration. The number of parts of a substance found in one million parts of a particular gas, liquid, or solid. Atmospheric $CO_2$ concentration is generally expressed in ppm.

## Part per billion (ppb)

A way of expressing very dilute concentrations. The number of parts of a substance found in one billion parts of a particular gas, liquid, or solid. Atmospheric concentrations of methane and nitrous oxide atmospheric are generally expressed in ppb.

## Precipitation

The term given to rain, drizzle, dew, hail, snow and other forms of moisture from the atmosphere that reach the ground.

## Pre-industrial

The period prior to 1750, before the Industrial Revolution. The Industrial Revolution marks the beginning of a strong increase in combustion of fossil fuels and related emissions of $CO_2$ and other greenhouse gases. Most of the increase in atmospheric $CO_2$ concentration occurred after 1950, with the strong industrial growth following the Second World War, a period sometimes called the ‘Great Acceleration’.

## Permafrost

Ground (soil or rock including ice and organic material) that remains at or below 0°C for at least two consecutive years. Permafrost contains almost twice as much carbon (largely in the form of methane) than currently in the atmosphere. When frozen

this carbon does not decompose. However, as permafrost thaws, the carbon contained in the frozen ground can be released into the atmosphere as methane and $CO_2$.

### Probabilistic

An approach that applies the principles of probability using available evidence and attempting to take into account uncertainty. A probabilistic climate projection measures the strength of evidence in different future climate change outcomes. This measure is dependent on the method used, is based on the current evidence available and encapsulates some of the uncertainty associated with projecting future climate change.

### Projections

A projection is a potential future quantity or set of quantities, often computed with the aid of a climate model. Projections are made for variables including greenhouse gas emissions, temperature, rainfall, and sea level. Projections involve judgments about the growth path of future global and domestic economies, policy actions, technological innovation and human behaviour. There are generally a range of projections for any given variable based upon a set of assumptions and uncertainties.

### Radiative forcing (forcing)

A measure of the influence of a particular factor (e.g. greenhouse gas, aerosol, or land-use change) on the net change in the Earth's energy balance. This balance determines the Earth's average temperature; positive forcing warms and negative forcing cools the Earth.

### Risks

The probability that a situation will produce harm under specified conditions. It is a combination of the probability that an event will occur and the consequences of the event.

In considering climate change risks there is a relationship between risks and actual impacts. Impacts depend on many other non-climatic factors, such as the exposure of people, infrastructure or ecosystems to the weather event or shift in climate; their sensitivity to the climatic changes; and their capacity to adapt. Together risks and adaptive capacity largely determine vulnerability to shifts in climate and changes in extreme weather events. Adaptation and mitigation are two of the broad, complementary approaches to managing climate change risks.

### Sea ice

Frozen ocean water that forms, grows, floats and melts in the ocean. In contrast, icebergs, glaciers, ice sheets, and ice shelves all originate on land. Sea ice occurs in both the Arctic and Antarctic. Sea ice grows during the winter months and melts during the summer months, but some sea ice remains all year in certain regions.

### Sea surface temperature

The temperature of the top layer (up to 10 metres) of the ocean.

### Snowpack

The total amount of snow and ice on the ground. In high mountain ranges and other cold places, snowpack builds up in the winter and melts in the spring and summer.

# GLOSSARY

### Storm surge

A rise above the normal sea level resulting from strong onshore winds and/or reduced atmospheric pressure. Storm surges typically accompany tropical cyclones as they make landfall but can also be formed by intense low-pressure systems in non-tropical areas, such as 'east coast lows' in the Tasman Sea.

### Uncertainty

An expression of the degree to which a value or relationship is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. Uncertainty can be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgment of a team of experts.

Also see *Confidence*.

### Very cold day

In Australia the Bureau of Meteorology defines a very cold day as a day with maximum temperature less than 5°C.

### Very hot day

In Australia the Bureau of Meteorology defines a very hot day as a day with maximum temperature greater than 40°C.

### Vulnerability

The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a result of the type, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its ability to adapt.

### Weather

The atmospheric variables (temperature, wind, precipitation etc.) for a brief period of time. Weather is what is experienced on a day-to-day basis.

### Water vapour

Water present in the atmosphere in gaseous form. Water vapour is an important part of the natural greenhouse effect and is the most abundant greenhouse gas. Water vapour affects the temperature of the planet; clouds form when excess water vapour in the atmosphere condenses. Water vapour has a very short lifetime in the atmosphere, and is usually considered as a 'fast feedback' to more long-term changes in radiative forcing.

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# COMMON QUESTIONS ABOUT CLIMATE CHANGE

### What is climate change?

Climate change is any significant change in the measures of climate lasting for several decades or longer, including changes in temperature, precipitation, or wind patterns. Historically, the Earth's climate has changed continually, but it is widely agreed that the observed changes over the past 50 years or so have been primarily caused by human activities.

i For further information refer to *1. The science of climate change.*

### How much has the global temperature changed?

Long-term air and ocean temperature records clearly show that the Earth is warming. Over the past century, the global air temperature has increased by about 0.8°C. From about 1970, the air temperature trend has strongly increased. The oceans are absorbing around 90% of the additional heat, with ocean heat content showing strong increases; on average the temperature of the ocean layer 0-700 m increased by 0.18°C between 1955 and 2010.

i For further information refer to *2.1 Observations of a changing climate.*

### Why does only a few degrees of warming matter?

Warming of a few degrees in average temperature may seem minor, but it is much larger than any of the climatic changes experienced during the past 10,000 years. The increase in average temperature creates a much greater likelihood of very hot weather and a much lower likelihood of very cold weather. A warming of only a few degrees in average temperature means we will see weather events that have never been observed since instrumental records were begun, and heat events that were rare in the previous climate will become more common. For comparison, the difference in global average air temperature between an ice age and a warm period in recent Earth history is only 5 to 6°C.

i For further information refer to *2.4 Back to the future: Insights from past climate changes* and *3.1 Changes in the climate system that cause impacts.*

### How are human activities contributing to climate change?

Human activities, particularly the burning of fossil fuels, agriculture and land clearing, are increasing the concentration of greenhouse gases in the atmosphere. This increase in greenhouse gases is enhancing the greenhouse effect, which in turn is warming the Earth.

i For further information refer to *1.2 How are human activities changing the climate?*

### How is the climate expected to change in the future?

Scientists expect that global warming and associated changes will continue if greenhouse gas emissions keep rising. It is very likely there will be continue to be increases in air and ocean temperatures, changing rainfall patterns, rising sea level and increasing intensity and frequency of many extreme weather events through the 21st century. However, reducing greenhouse gas emissions now and in the coming decades will have a major influence on

the degree of climate change that occurs, particularly in the second half of this century and beyond.

i For further information refer to *2.2 Projections of future change*.

### How does climate change affect us?

Changes have already been observed in our climate and have caused serious impacts in Australia. There has been an increase in the number of hot days and record-breaking heatwaves and in heavy rainfall events.

Climate change is likely to continue to affect Australians in a number of ways, including:

- rising temperatures and more hot days
- greater risk of bushfire
- increased frequency and severity of extreme weather events including heavy rainfall and drought
- sea-level rise leading to more coastal flooding and erosion.

i For further information refer to *3. Risks of a changing climate*.

### How do scientists know the climate is changing?

Scientists collect detailed and accurate data on the climate system, including air and ocean temperature, precipitation, sea level, ocean salinity and acidity, changes in ice sheet mass, to name just a few. Direct measurements of temperature and precipitation have been taken for over 150 years. Since the 1970s satellites have measured global temperatures and since the 1990s global sea level. Proxy records such as ice cores, tree rings, marine sediments, pollen and others provide insights into the climate of hundreds or thousands of years ago. Analysis of this climate data is used to put today's climate change in a longer term context and to explore the response of the climate system to changes in radiative forcing in the past.

i For further information refer to *2.1 Observations of a changing climate* and *2.4 Back to the future: Insights from past climate changes*.

### How is the warming observed over the last century different from previous changes in the Earth's climate?

The most significant difference between recent warming and previous changes in the Earth's climate is the speed of the change, and the role of humans in changing greenhouse gas concentrations. Ice cores from Antarctica provide a record of 800,000 years of atmospheric $CO_2$; in all that time the concentration has never increased so quickly and by so much as during this era of human influence; the so-called 'Anthropocene'.

i For further information refer to *1.3 How are humans changing the climate?*

### How do scientists make projections of the future climate?

Scientists estimate how the climate may change in the future using knowledge of climate system processes, how the climate is affected by increasing concentrations of greenhouse gases, observations of past changes and scenarios of future changes in greenhouse gas concentrations. Scientists integrate this knowledge using climate models – mathematical representations of the climate system. The models simulate the behaviour of the climate system and project possible futures under different scenarios of greenhouse gas levels.

i For further information refer to *2.2 Projections of future change*.

### How reliable are climate models?

Climate models are the best tools that we have for projecting future climate change. They are based on laws of physics; they have been tested against observational data and accurately represent many features of current and past climate, including observed changes over the past century. Climate models are continuously improving in their abililty to simulate the behaviours of the climate system, building more confidence in their projections of the future.

i For further information refer to *Box 3: How do climate models work?*